A poster for the "Module of Opportunity for DUNE". The background is a dark blue with a pattern of lighter blue circles. The text is in white and orange. It includes the title "Module of Opportunity for DUNE", the dates "November 12-13, 2019", and the location "Location: Brookhaven National Laboratory". A smaller version of the DUNE logo is also present on the right side of the poster.

Module of Opportunity
for DUNE
November 12-13, 2019
Location: Brookhaven National Laboratory

ARAPUCA:

from “*an emerging technology*” into
“*the technology choice*”
... and beyond

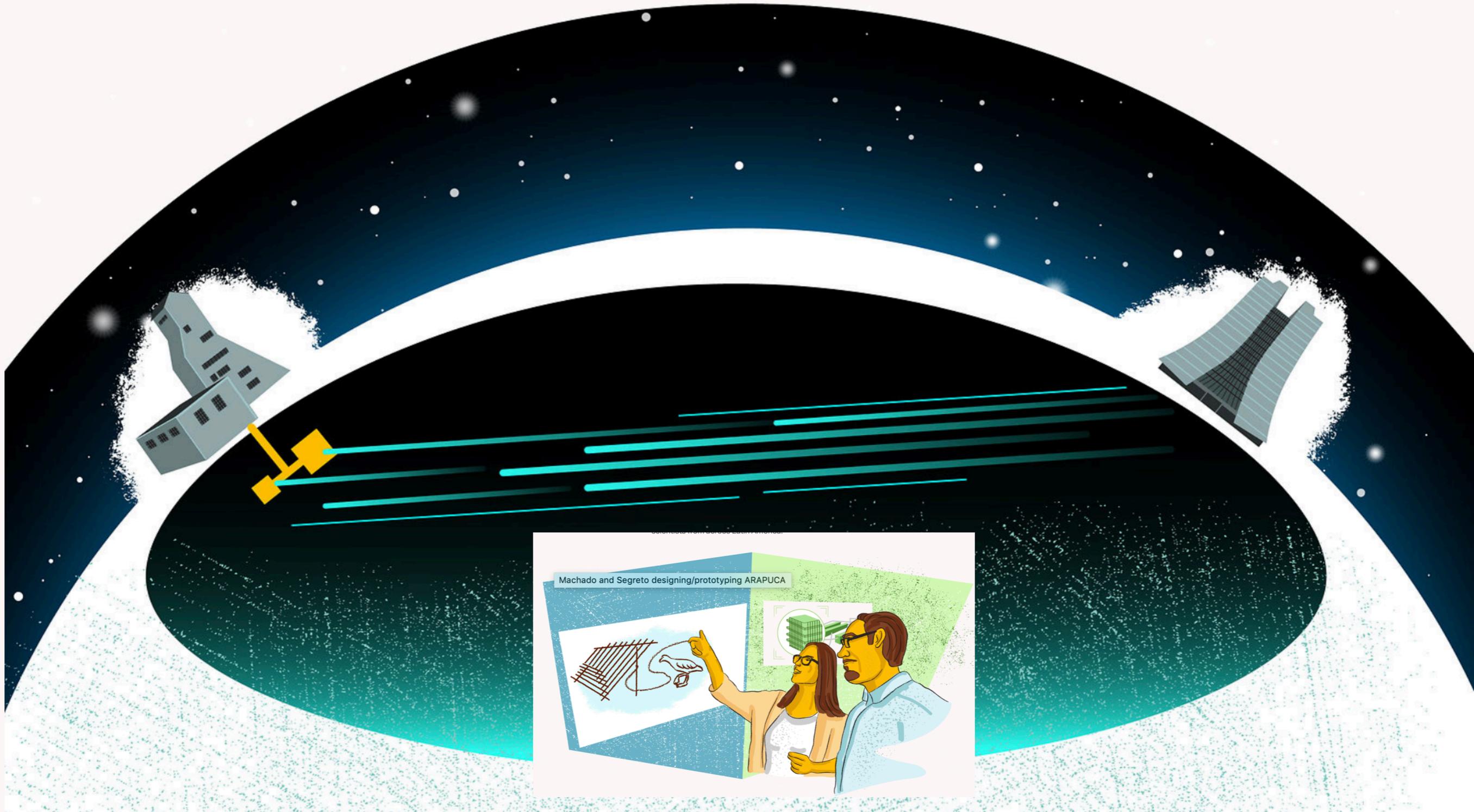


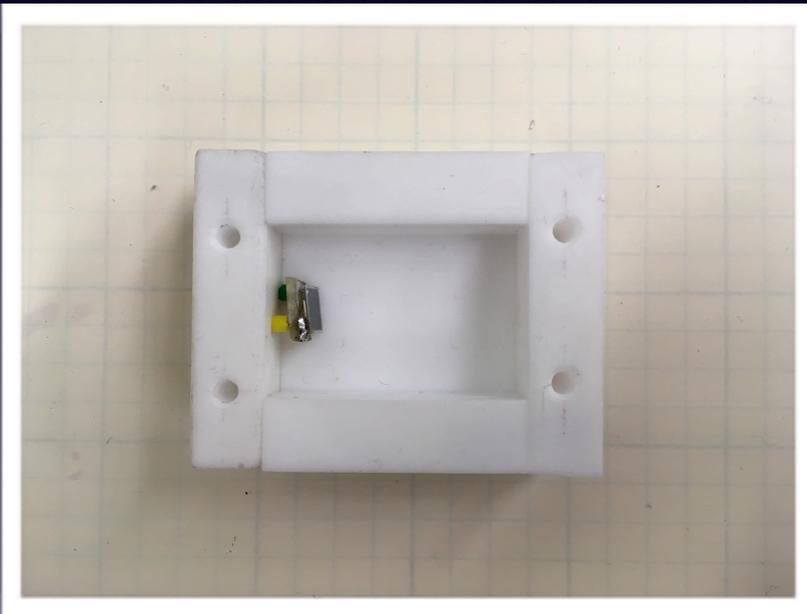
Illustration by Sandbox Studio, Chicago with Pedro Rivas

ARAPUCA: Let there be light traps

10/24/19 | By Lauren Biron

Latin American institutions are instrumental in creating photon detectors for the Deep Underground Neutrino Experiment.

July 2016
DUNE - PDS Review



One of the first
ARAPUCA prototypes

Proposal for ProtoDUNE Photo Detection System. ARAPUCA: an alternative light collection system

E. Segreto¹, A.A. Machado^{1,3}, C. O. Escobar^{2,1}, E. Kemp¹, and G. A. Valdivieso⁴

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²*Fermi National Accelerator Lab, Batavia, IL 60510-0500, USA*

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⁴*University Federal of Alfenas em Poços de Caldas, 11999, CEP 37715-900 Poços de Caldas-MG, Brazil*

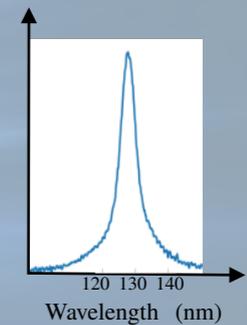
Abstract

We propose a new device, named ARAPUCA, for the **detection of liquid argon scintillation light**, which is realized through the coupling of an **innovative passive photon collector with an array of silicon photomultipliers**. It is an ideal device to be installed in large time projection chambers, since it will allow to reach **reasonable detection efficiencies**, at the level of percent, **on large areas** (order of 1 m²), with the use of a limited number of active sensors. We propose to install an array of **ARAPUCAs inside the ProtoDUNE detector**, in view of its test at CERN, with the objective of demonstrating the improvement in light yield that could be achieved with the use of these devices The ARAPUCA array will also allow to perform a **better spatial reconstruction of the ionizing** events with respect to bars, since it is composed by discrete elements.

ARAPUCA LIGHT TRAP

Liquid Ar

VUV - 128 nm



pTerP UV-A - 350 nm

Dichroic Glass

Transmission

Reflection

Blue - 430 nm

TPB

Reflective surface

Reflective surface

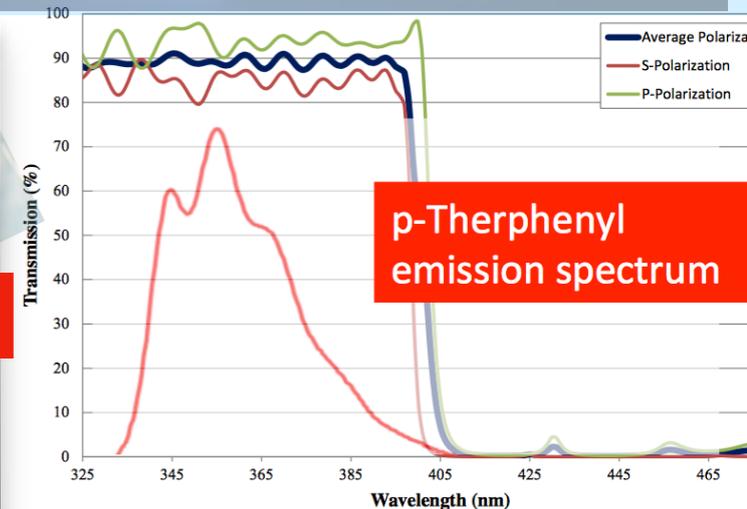
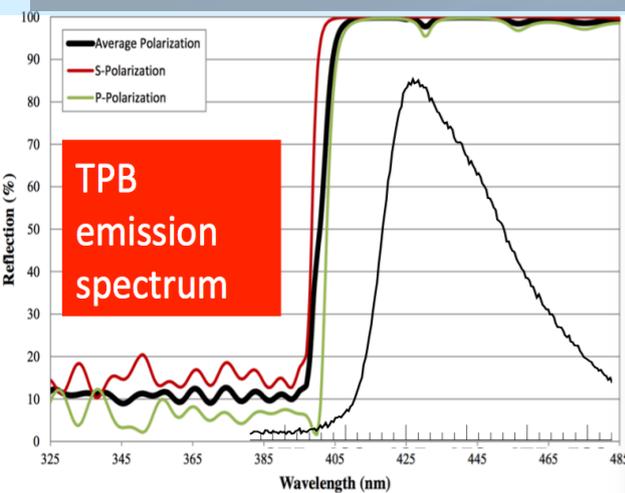
ARAPUCA Cell

Reflective surface

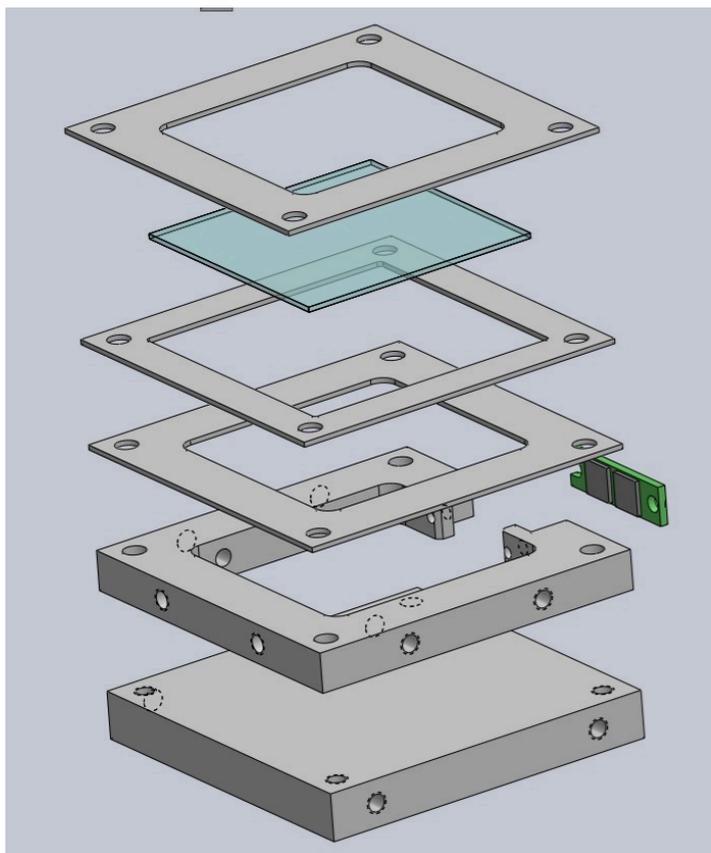
Reflective surface

PhotoSensors

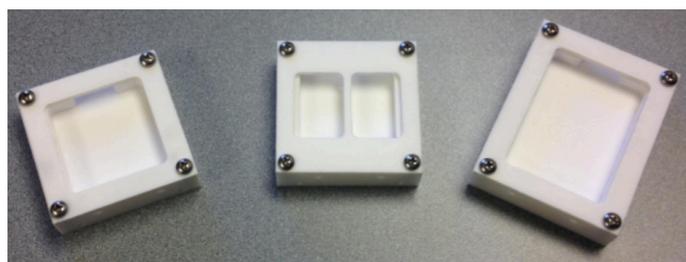
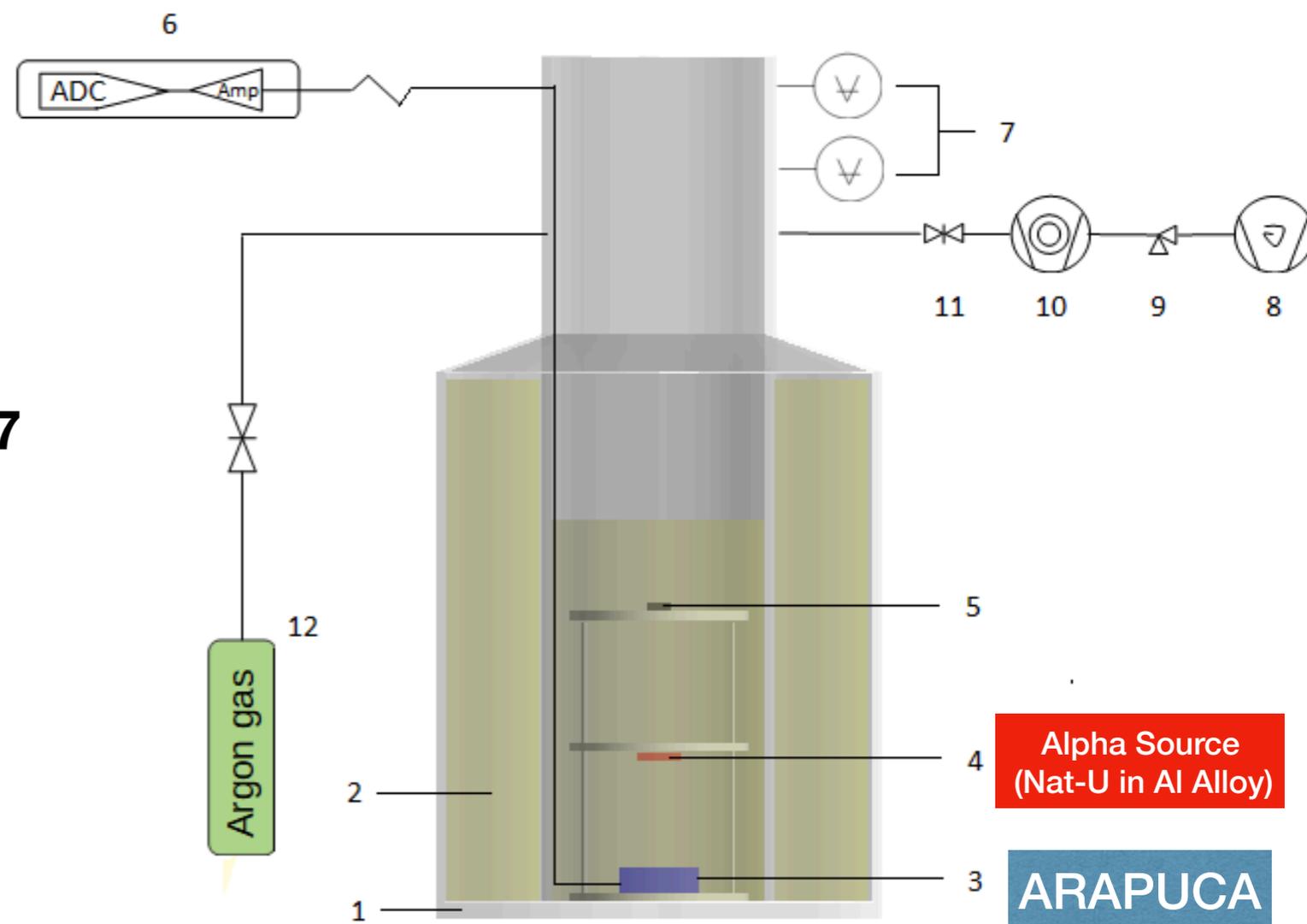
with single Photon Counting sensitivity



First measurement of global detection efficiency of an ARAPUCA prototype to liquid Argon scintillation light [E. Segreto et al, 2018 JINST 13 P08021]



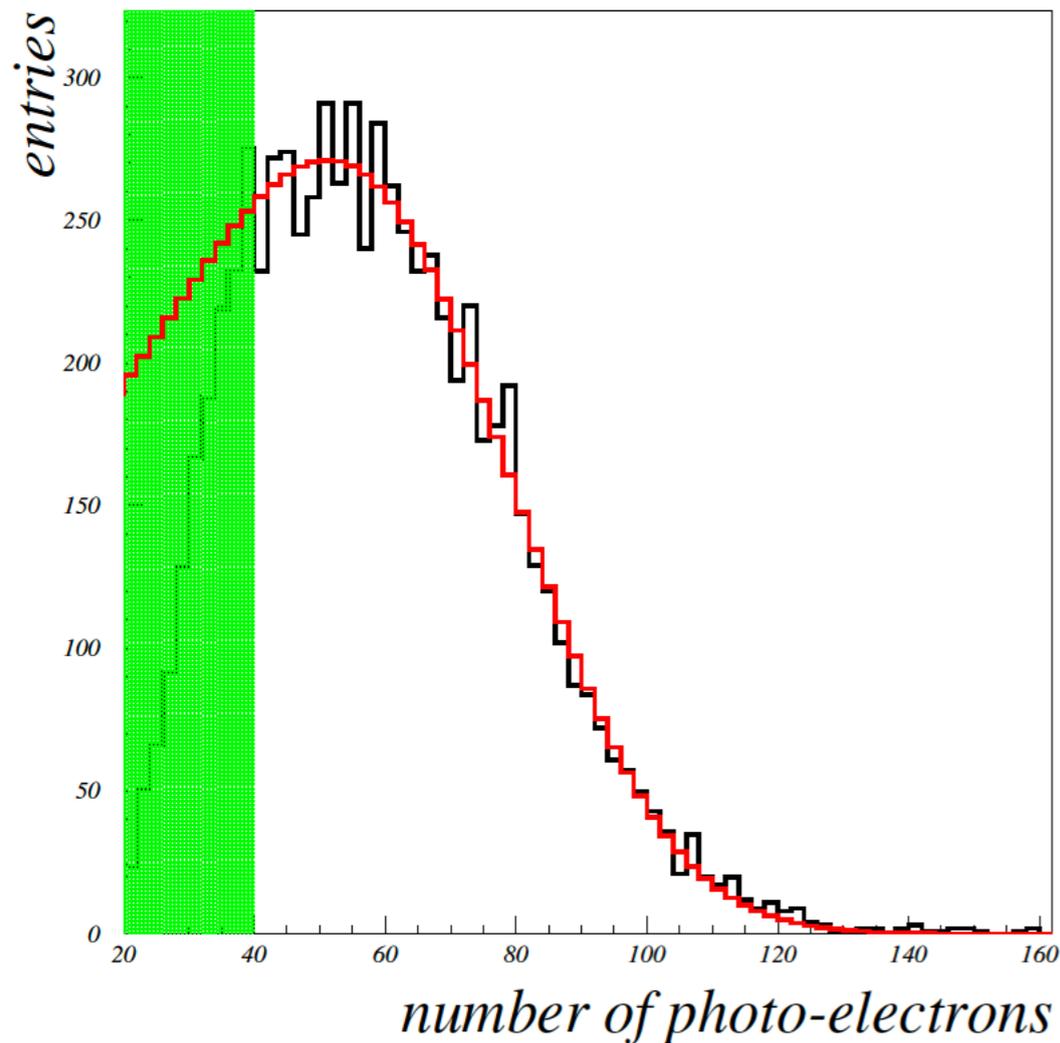
Fall 2016-
Spring 2017



- PTFE box: internal dimensions of 3.6 cm 2.5 cm 0.6 cm
- Window: dichroic filter with dimensions of 3.6 cm X 2.5 cm, cut-off at 400 nm.
- WLS coating: external side p-Terphenyl (pTP), internal side TetraPhenyl-Butadiene (TPB).
- Prototype acceptance window: 9 cm², read-out: single SiPM (active area 0.36 cm²)
- $S_{SiPM}/S_{Dichroic} = 4\%$



Alpha Spectrum and Efficiency



Illumination (pointlike Alpha Source)

$$PH = Y_{\gamma} q_{\alpha} E_{\alpha}(^{238}\text{U}) f_{\Omega} \simeq 6060 \gamma$$

$$PE(^{238}\text{U}) = 71 \pm 1 \text{ phel}$$

from Fit of α spectrum (in PE)

Correction Factors:

- Cross-talk (15%)
- Reflectivity of the internal surfaces (8-10%)
- Slightly deteriorated pTP Film (10-15%)

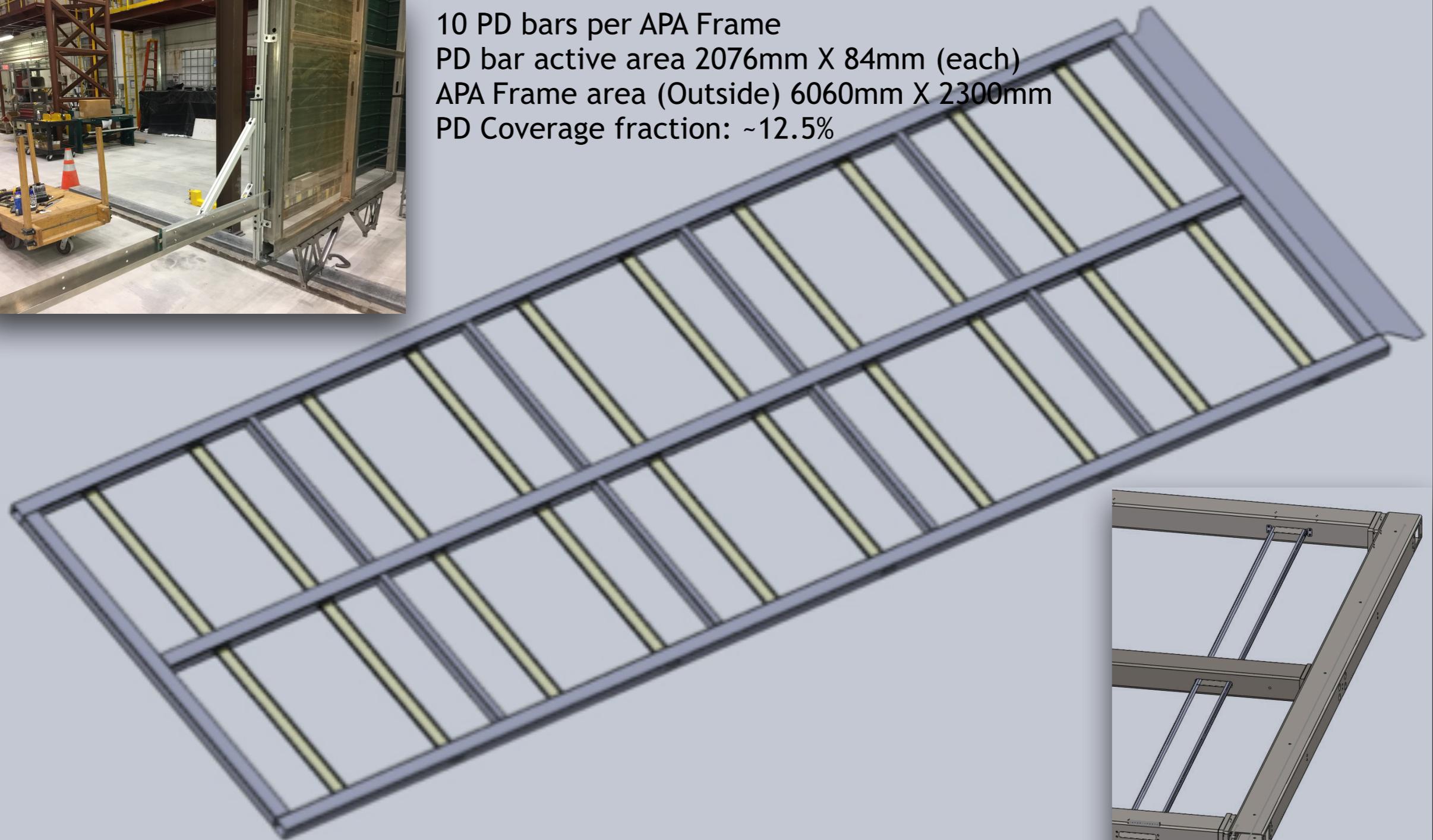
The total ARAPUCA efficiency, ϵ_{α}^A estimated through the α particle sample is:

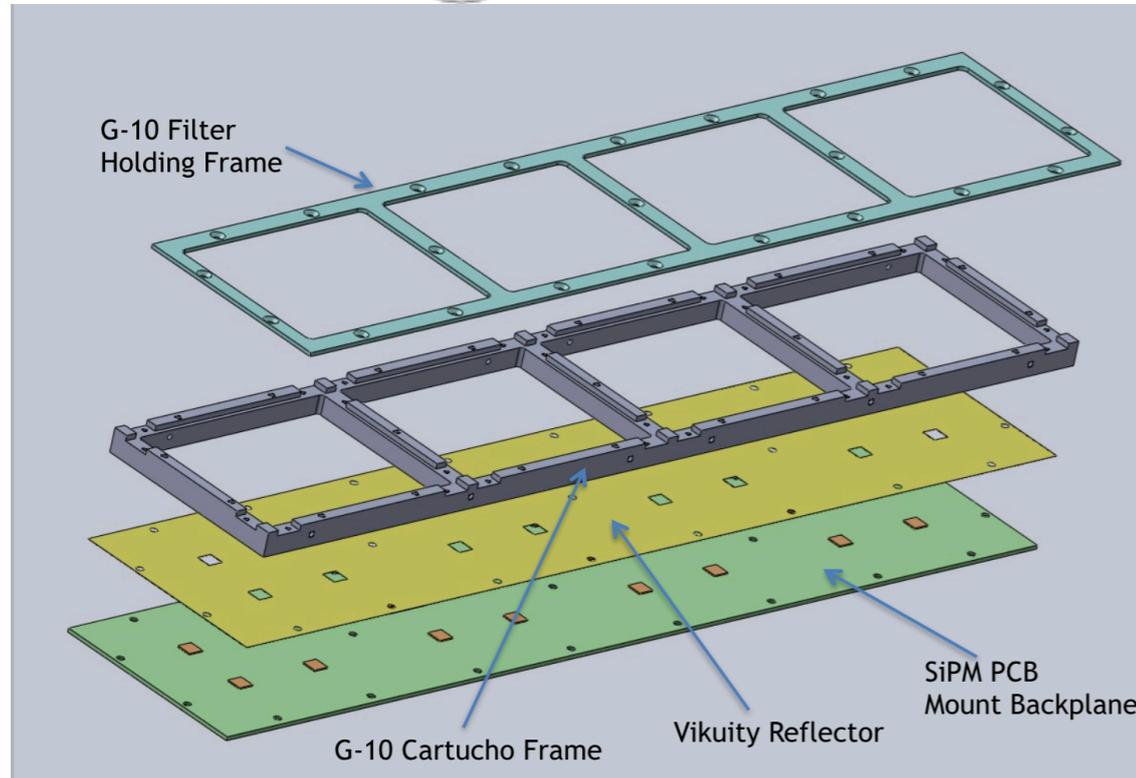
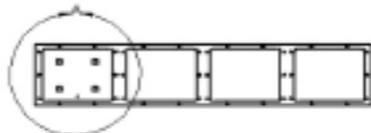
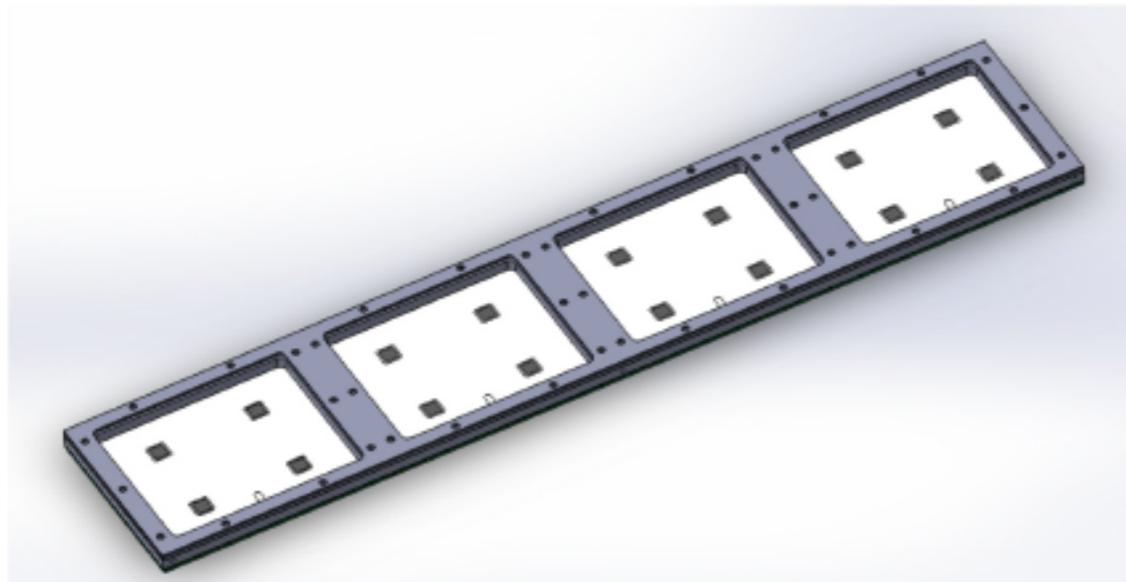
$$\epsilon_{\alpha} = \frac{PE}{PH} = 1.0\% \pm 0.2\%$$

DUNE FD MODULE 1 SP - PHOTODETECTOR DESIGN: BAR-SHAPED PH-COLLECTOR MODULES INSERTED THROUGH SLOTS INTO APA FRAME



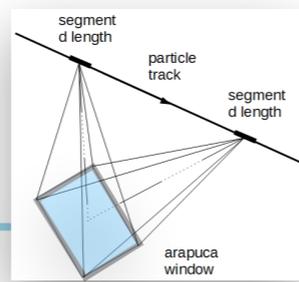
10 PD bars per APA Frame
PD bar active area 2076mm X 84mm (each)
APA Frame area (Outside) 6060mm X 2300mm
PD Coverage fraction: ~12.5%





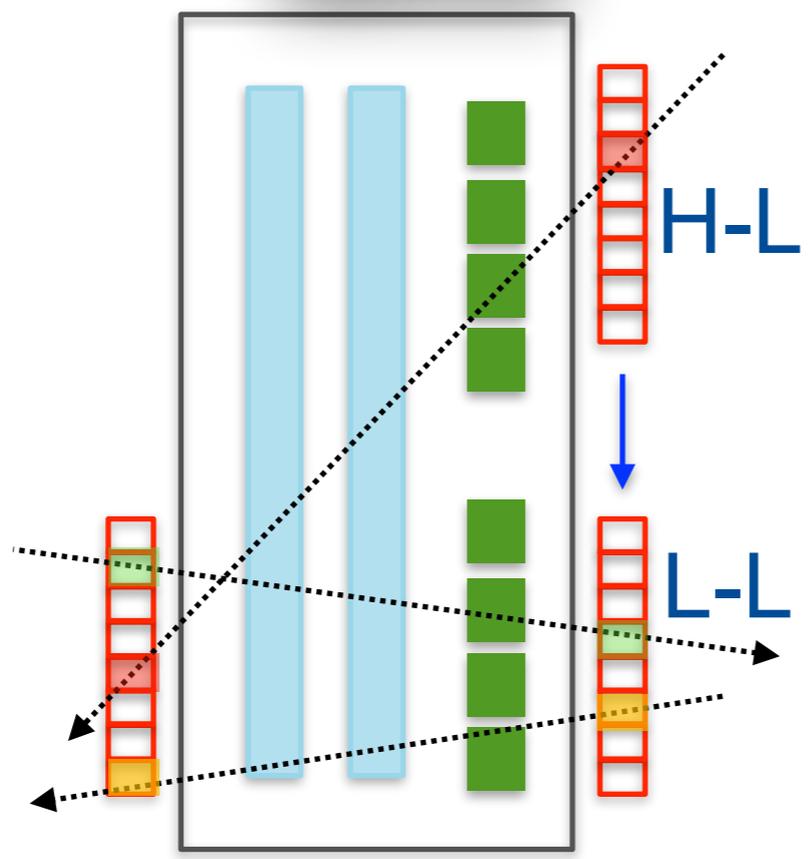
- Arrays of ARAPUCA cells to form a “Bar shaped” module to fit in the APA slot
- 4 SiPMs (6x6 mm²) in each ARAPUCA Cell (passive ganging) → one read-out channel
- Cell optical window: 9.8 x 7.8 cm²
- WLS coating: external side p-Terphenyl (pTP), internal side TPB on VIKUITI reflector
- $S_{SiPM}/S_{Dichroic} = 1.9\%$

A_{Ω} integrated angular Acceptance

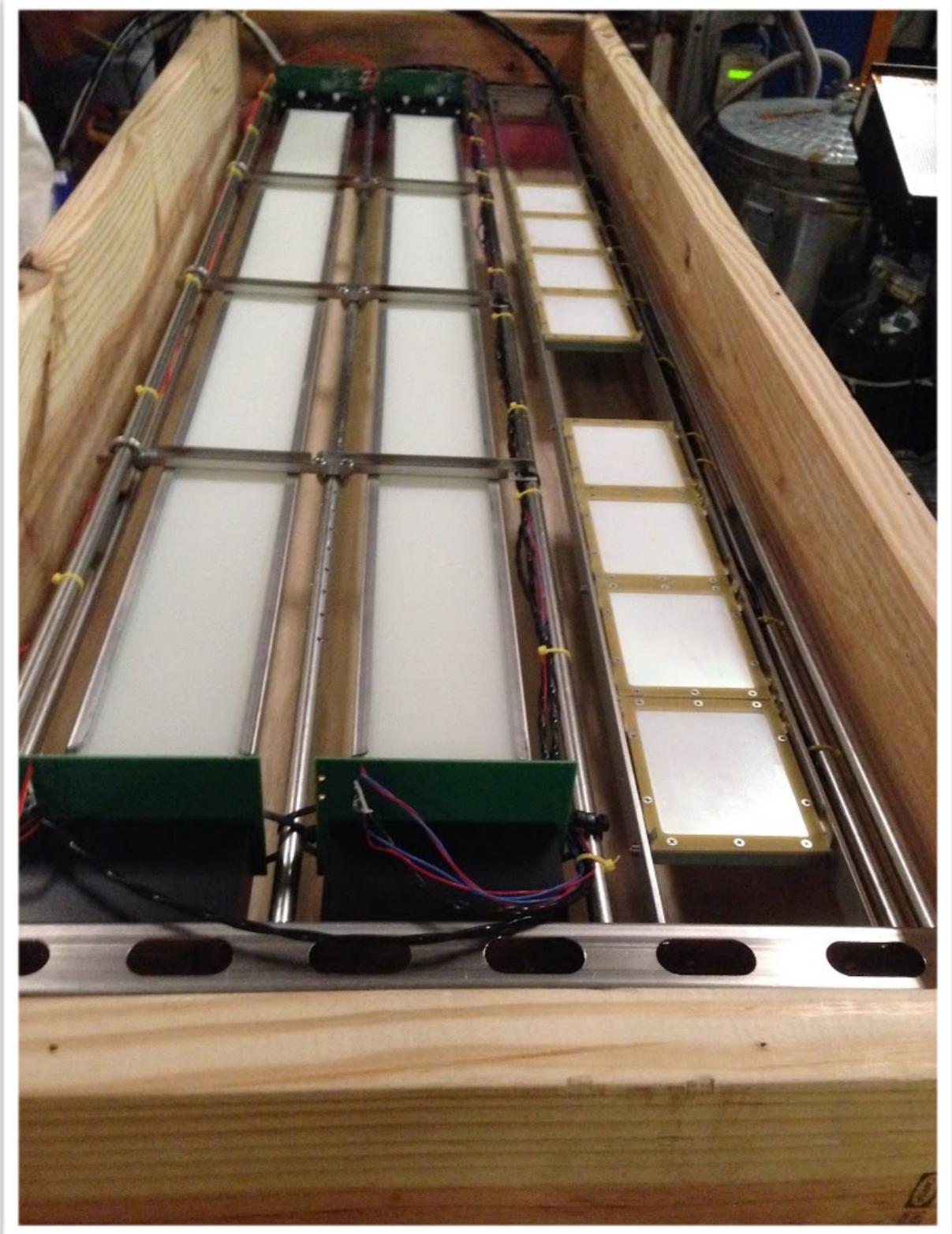


$$PH = A_{\Omega} \frac{1}{4\pi} \frac{dN^{\gamma}}{dx}$$

$$\frac{dN^{\gamma}}{dx} = Y_{\gamma} q_{mip} \left\langle \frac{dE}{dx} \right\rangle_{\mu} \rho_{Ar}$$



Fall 2017



- **Light source:** Scintillation from Cosmic Muons through LAr (Trigger & Tracking by external segmented hodoscopes)
- Total run time 366 hs (H-L) + 519 hs (L-L)

Results

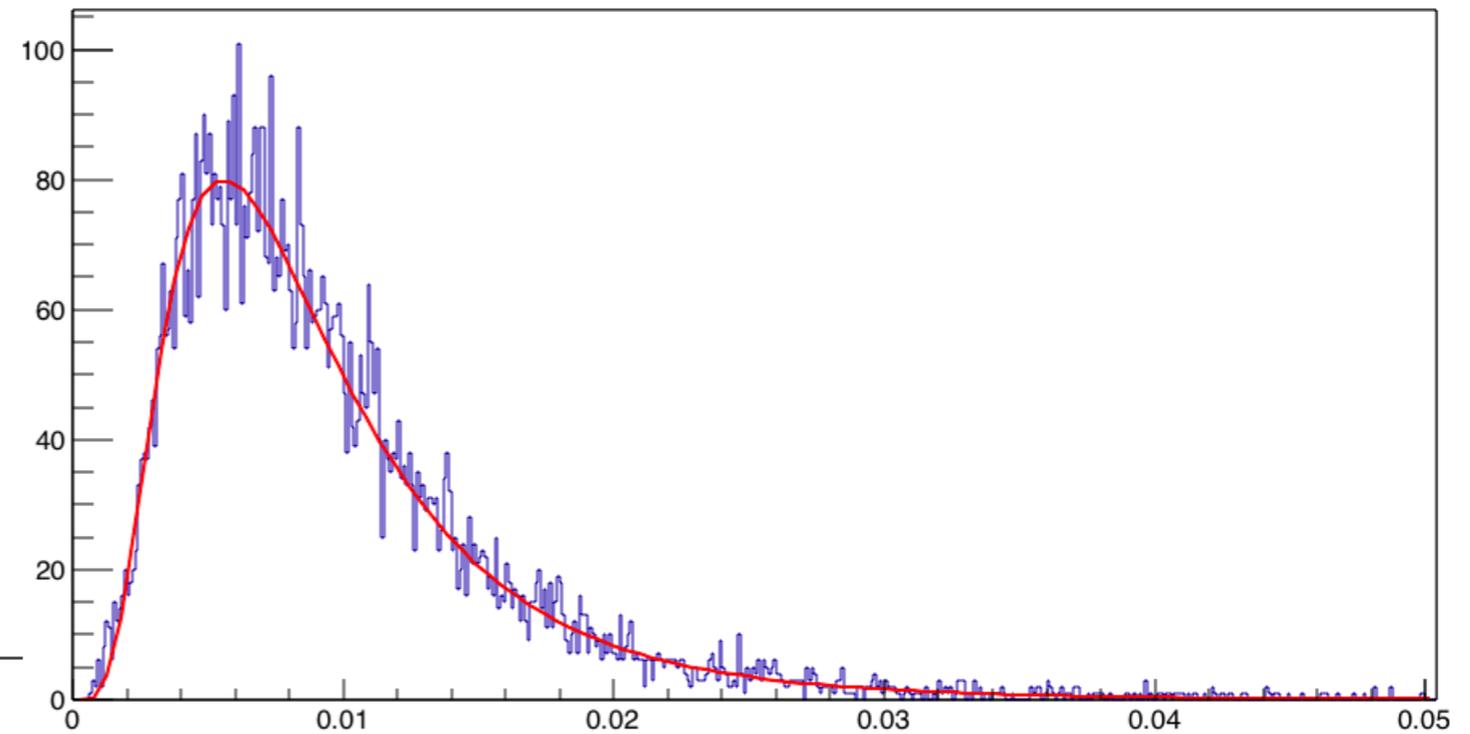
PE Spectra Cuts +
Light Pattern Cut:

$$\epsilon = \frac{PE}{PH}$$

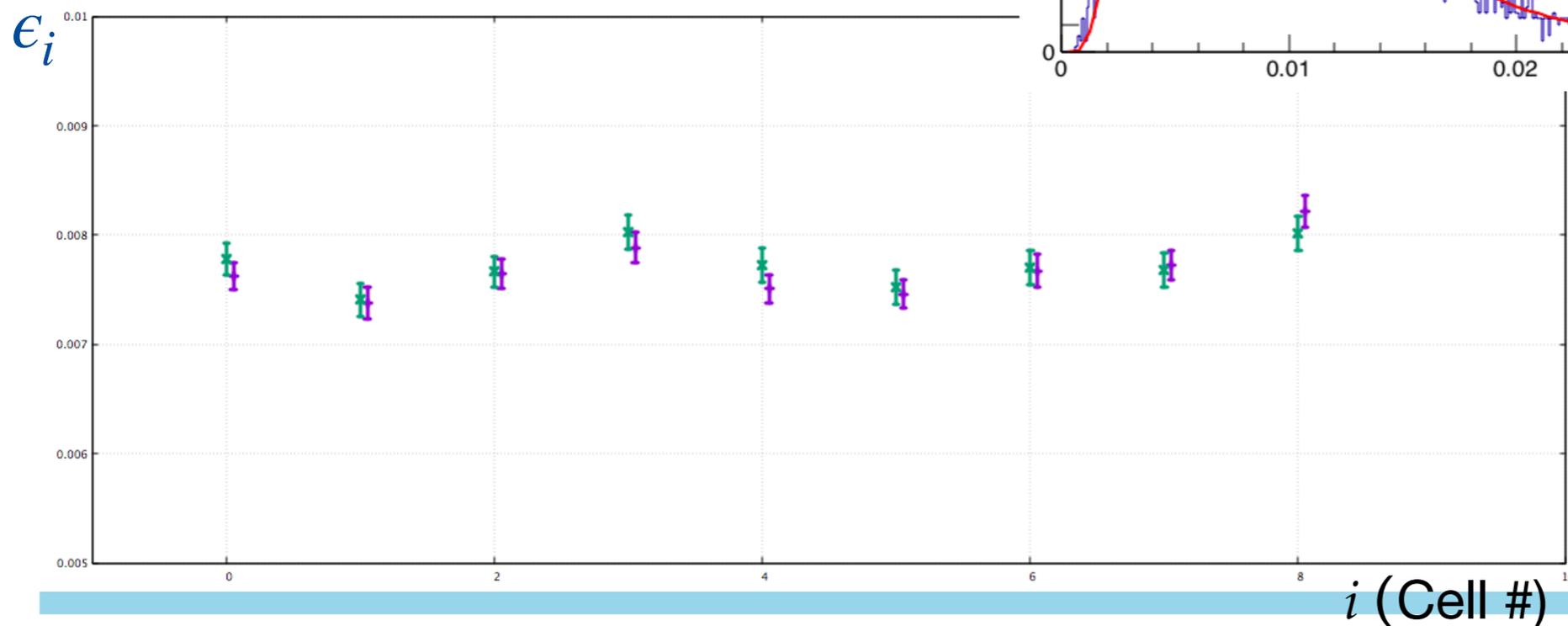
$$\text{Efficiency (\%)} = 0.777 \pm 0.033$$

Good Uniformity of Response from
ARAPUCA Cells

$$0.74 \leq \epsilon_i \leq 0.82$$



ϵ_{TOT}



Achievements so far:

- Demonstrated Efficiency in the % range
- Single Photon sensitivity and precise photon counting capability
- Large Area coverage within the (extremely) constrained geometry required for installation in DUNE FD Module-1
- Longitudinal Segmentation possible providing strong handle for pointing (space resolution)

next (necessary) step:

**ARAPUCA test with ProtoDUNE SP
at CERN Neutrino Platform**

**(Sept-Nov. 2018 w/ beams
Jan-Dec 2019 w/ Cosmics)**

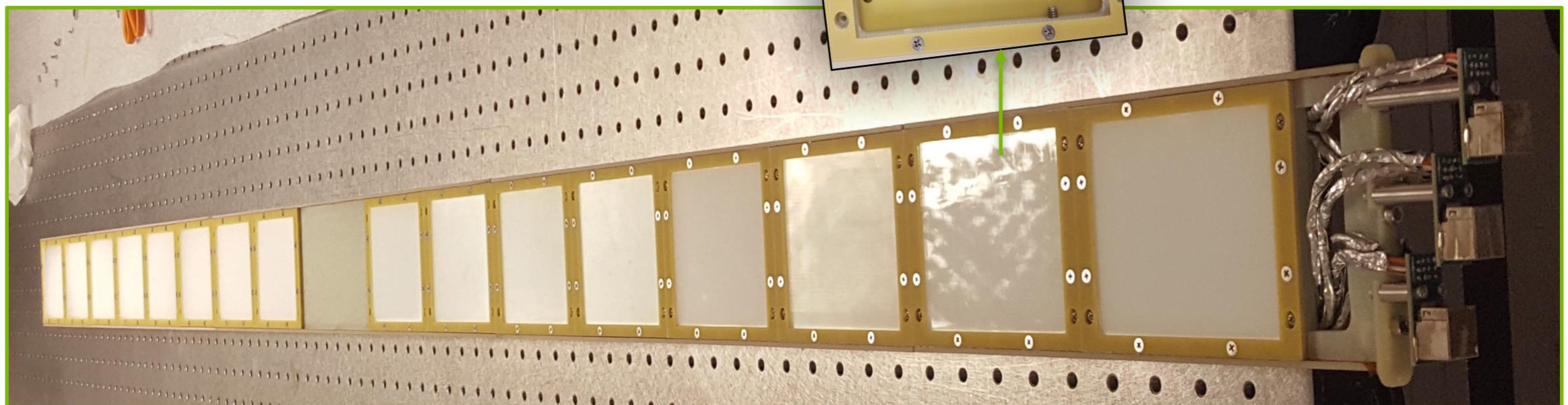
ARAPUCA PD design for protoDUNE

ProtoDUNE PDS Group - DUNE PD Consortium

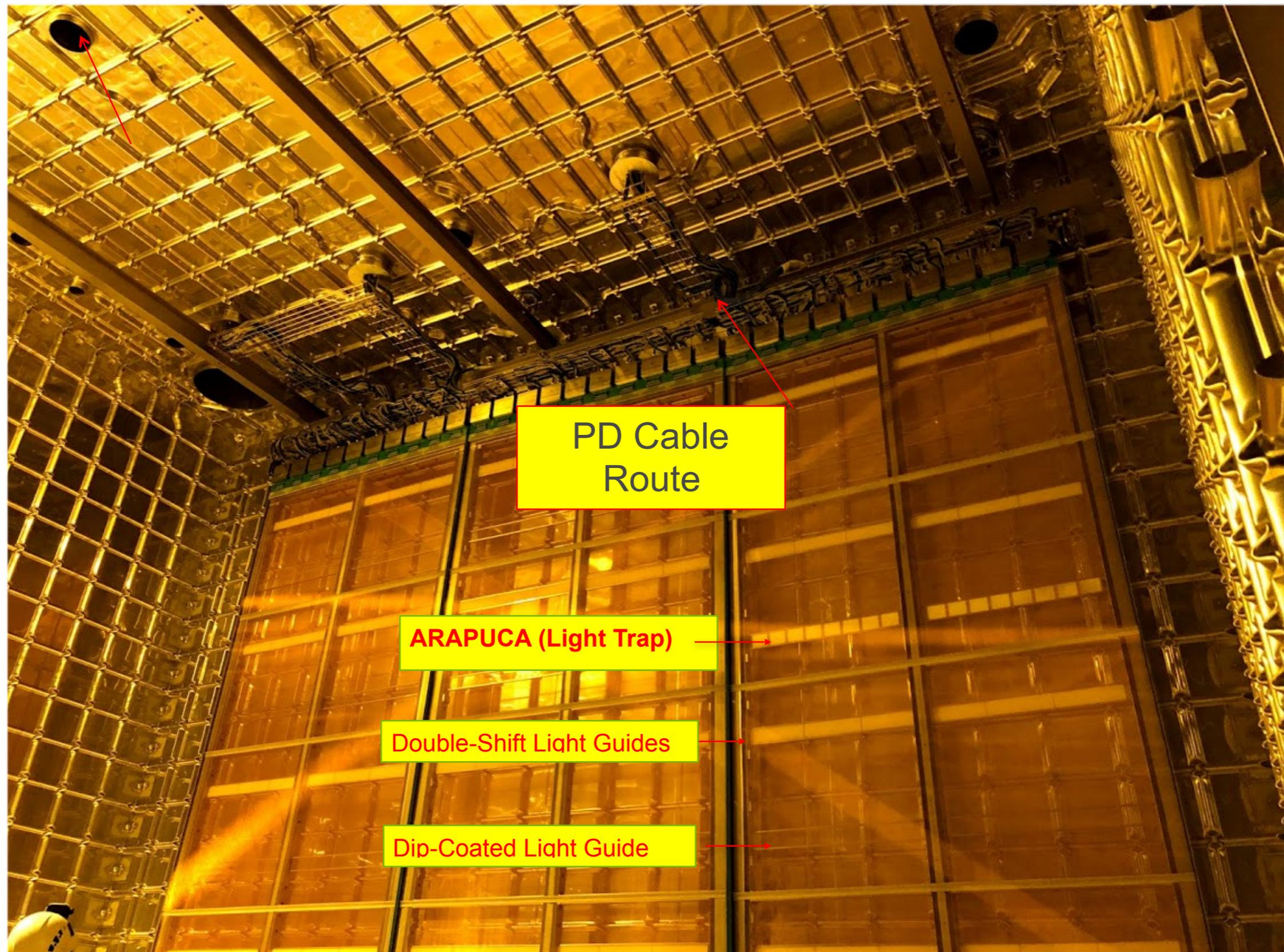
- 2 Bar Modules - one in beam side TPC, segmented along beam direction \
- 4 Cells per Array - 4 Arrays per Bar
- 12 (or 6) cryo-SiPMs per Cell - passively ganged
- Dichroic (short-pass) filter - optical window: 9.8 x 7.8 cm²
- p-TP deposited on outer surface of Dichroic glass, TPB on inner surfaces deposited on VIKUITI Reflective Foil
- $S_{SiPM}/S_{Dichroic} = 5.6\%$ (or 2.8%)

Cryo-SiPMs

One of the two ARAPUCA Modules installed with ProtoDUNE photon-detection system

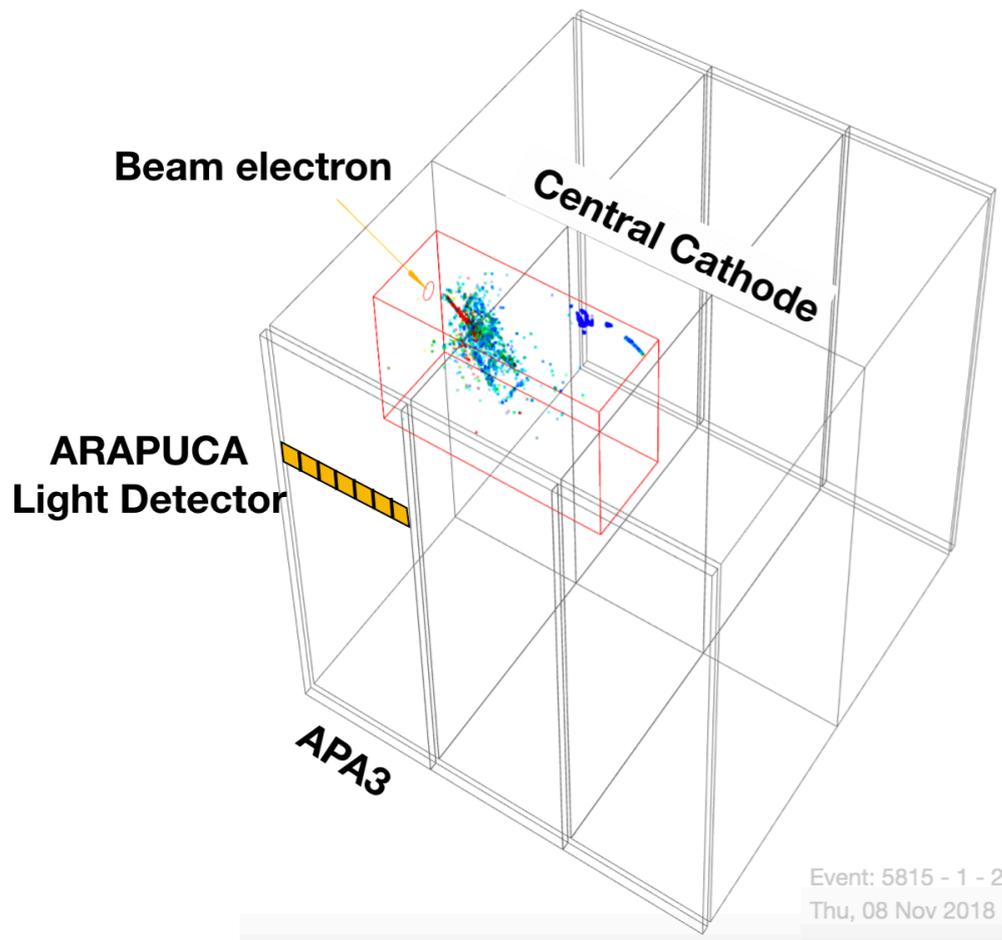


Photon-Detector in ProtoDUNE-SP



Large LAr detector operating at the CERN Neutrino Platform

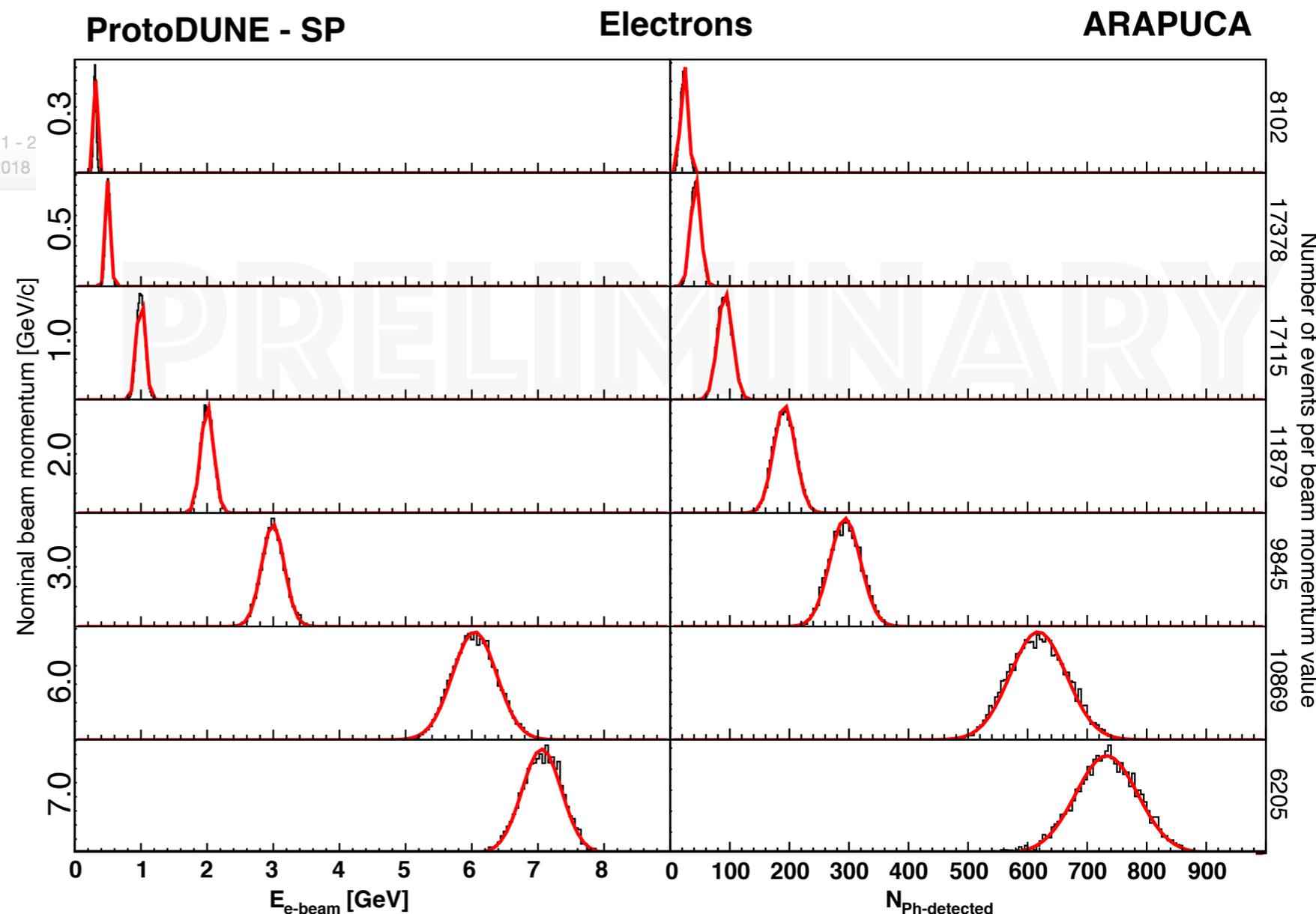
Operating on the H4-VLE charged particle test beam offers a first ever opportunity to directly probe the calorimetric response *with light* to EM and hadronic showers in the sub- to few-GeV momentum range.



calorimetric response from Light signal from a single ARAPUCA module (~0.5% photo-sensitive area coverage)

EM shower at ~3 m distance in the (drift) direction

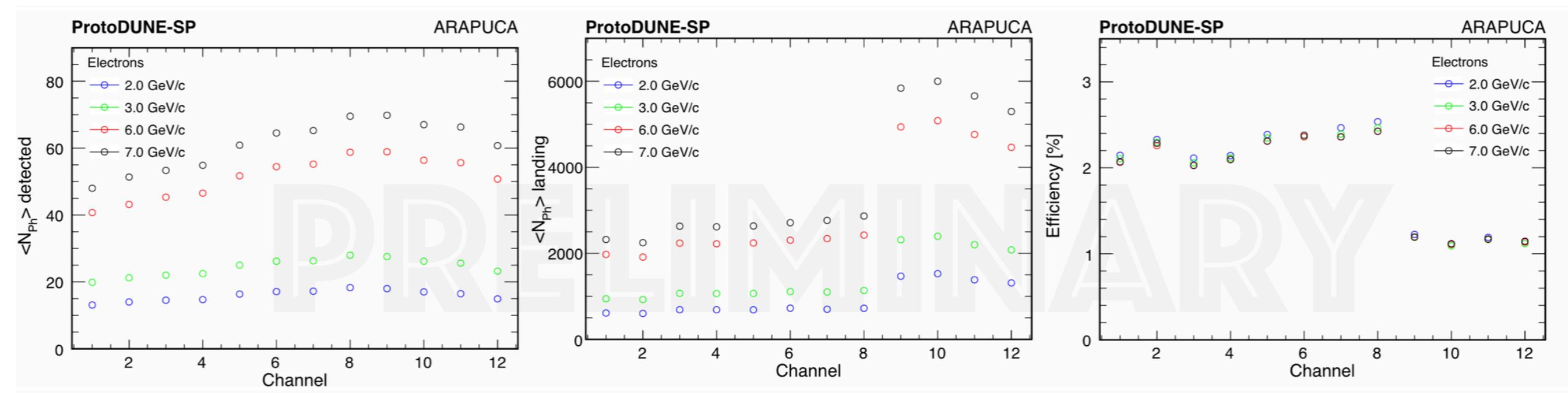
ProtoDUNE PDS Group - DUNE PD Consortium



Incident Electron momentum distribution

detected photons spectra

Detection efficiency of the ARAPUCA Bar (in APA3) - [12 cells]

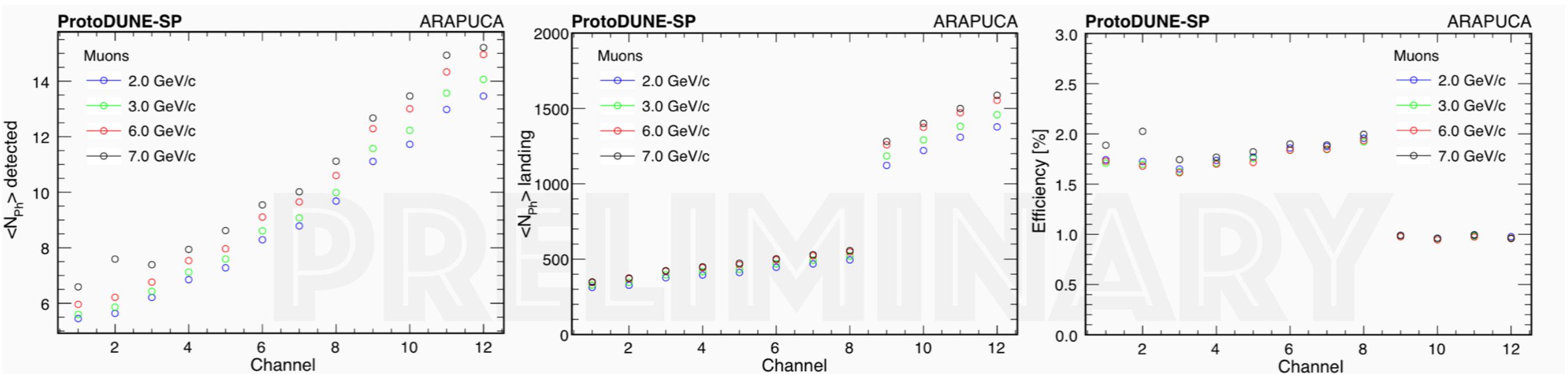


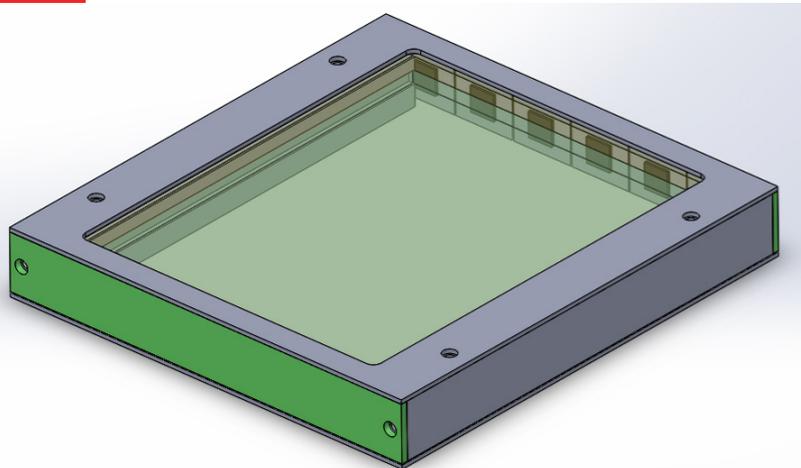
The detection efficiency of the ARAPUCA detectors in the ProtoDUNE-SP PD system is finally taken as the median value of the individual cells with its error:

$$\text{cell type-1 ; } \tilde{\epsilon}_1 = (2.05 \pm 0.27)\%$$

$$\text{cell type-2 ; } \tilde{\epsilon}_2 = (1.06 \pm 0.10)\%$$

where type-1 are cells $j = 1, \dots, 8$ in the ARAPUCA module and type-2 are those $j = 9, \dots, 12$ with

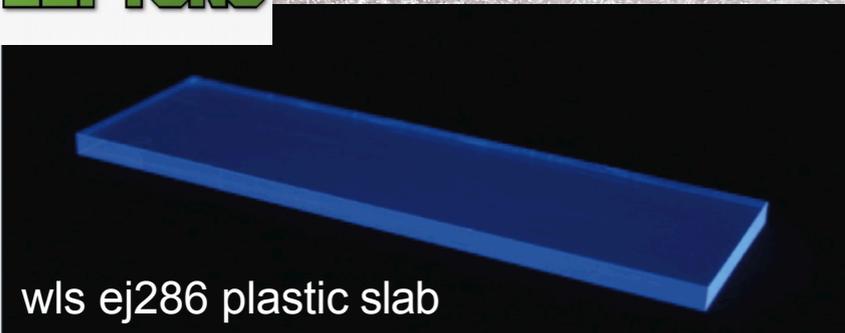




Two arrays of 4 HMMTS TSV MPPC



LAB LEPTONS

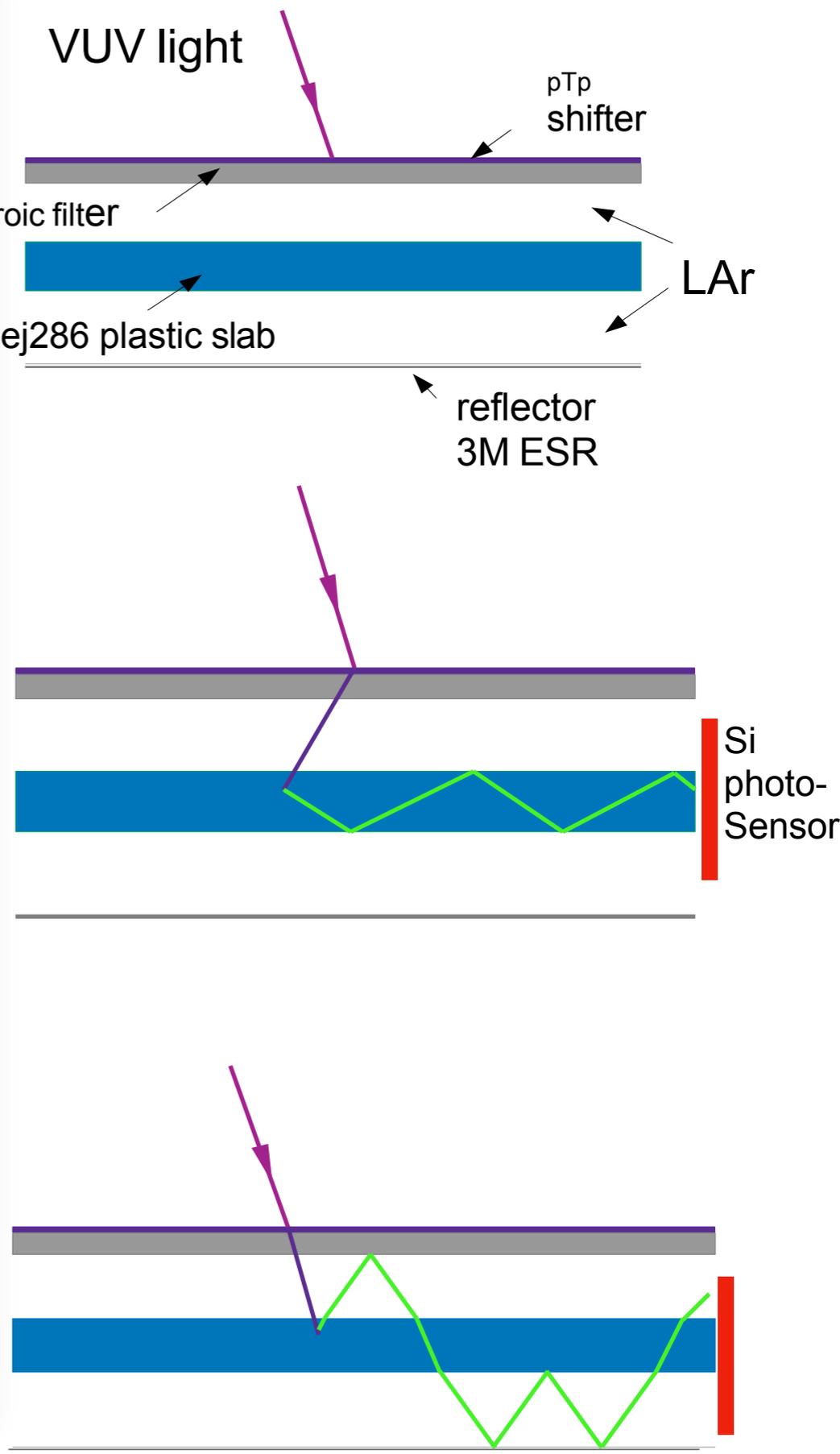


wls ej286 plastic slab

X-ARAPUCA

merging Double-Shift Light Guide & Light Trap

IMPLEMENTED IN SBND

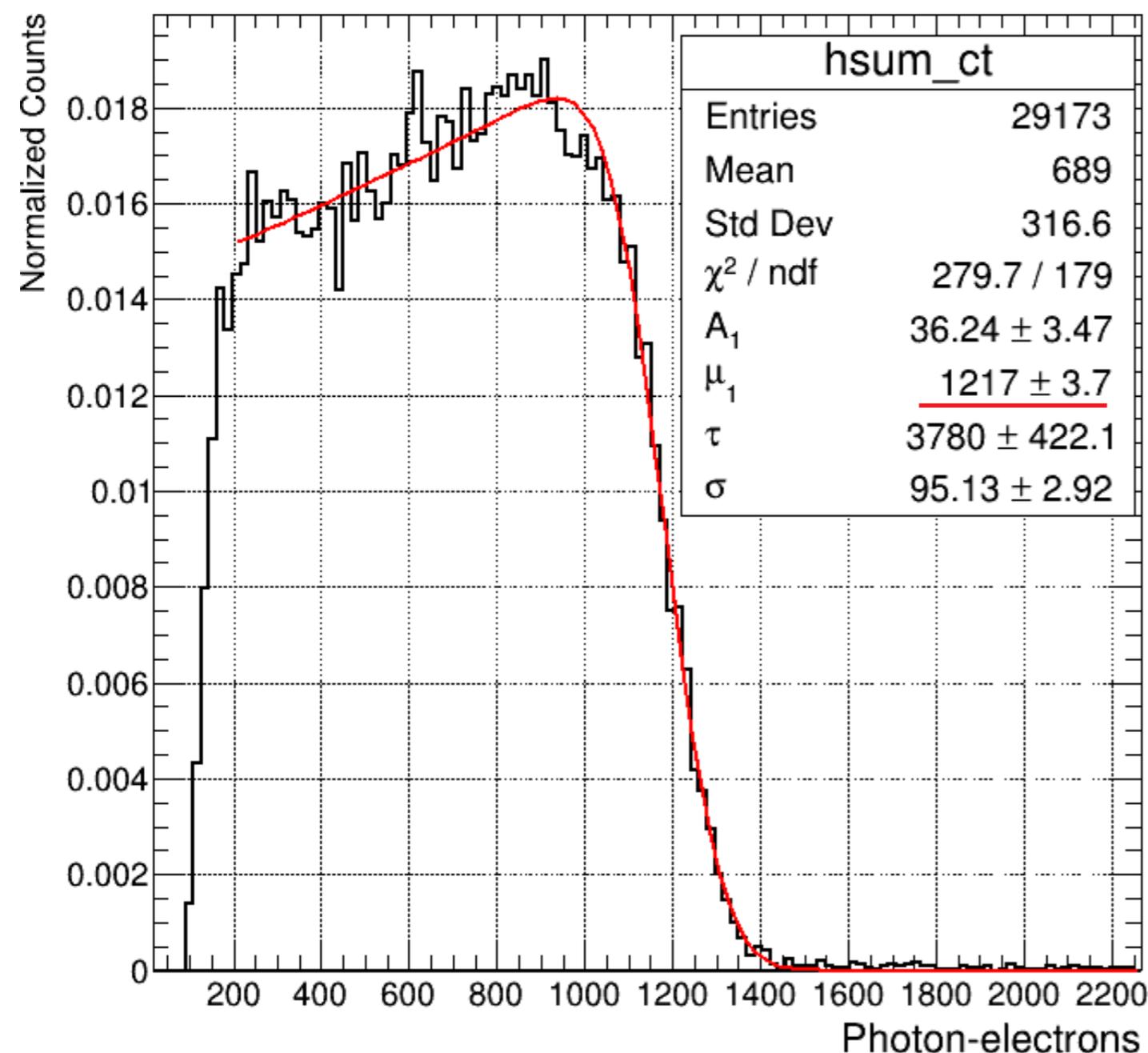


40% improvement on collection efficiency compared to standard ARAPUCA

Alpha Source Spectrum



$$F(E) = \sum_{i=1}^3 f(E - \mu_i; \sigma, \tau) = \sum_{i=1}^3 \frac{A_i}{2\tau} \exp\left(\frac{E - \mu_i}{\tau} + \frac{\sigma^2}{2\tau^2}\right) \operatorname{erfc}\left(\frac{1}{\sqrt{2}}\left(\frac{E - \mu_i}{\sigma} + \frac{\sigma}{\tau}\right)\right)$$



α energy (MeV)	relative intensity	parent nucleus
4.187	48.9%	^{238}U
4.464	2.2%	^{235}U
<u>4.759</u>	<u>48.9%</u>	^{234}U

$$N_{\gamma}^A = N_{\gamma}^{LAr} \times E_{\alpha} \times q_{\alpha} \times \Omega^A$$

$$= 51000 \text{ Ph/MeV} \times 4.759 \text{ MeV} \times 0.71 \times 0.225$$

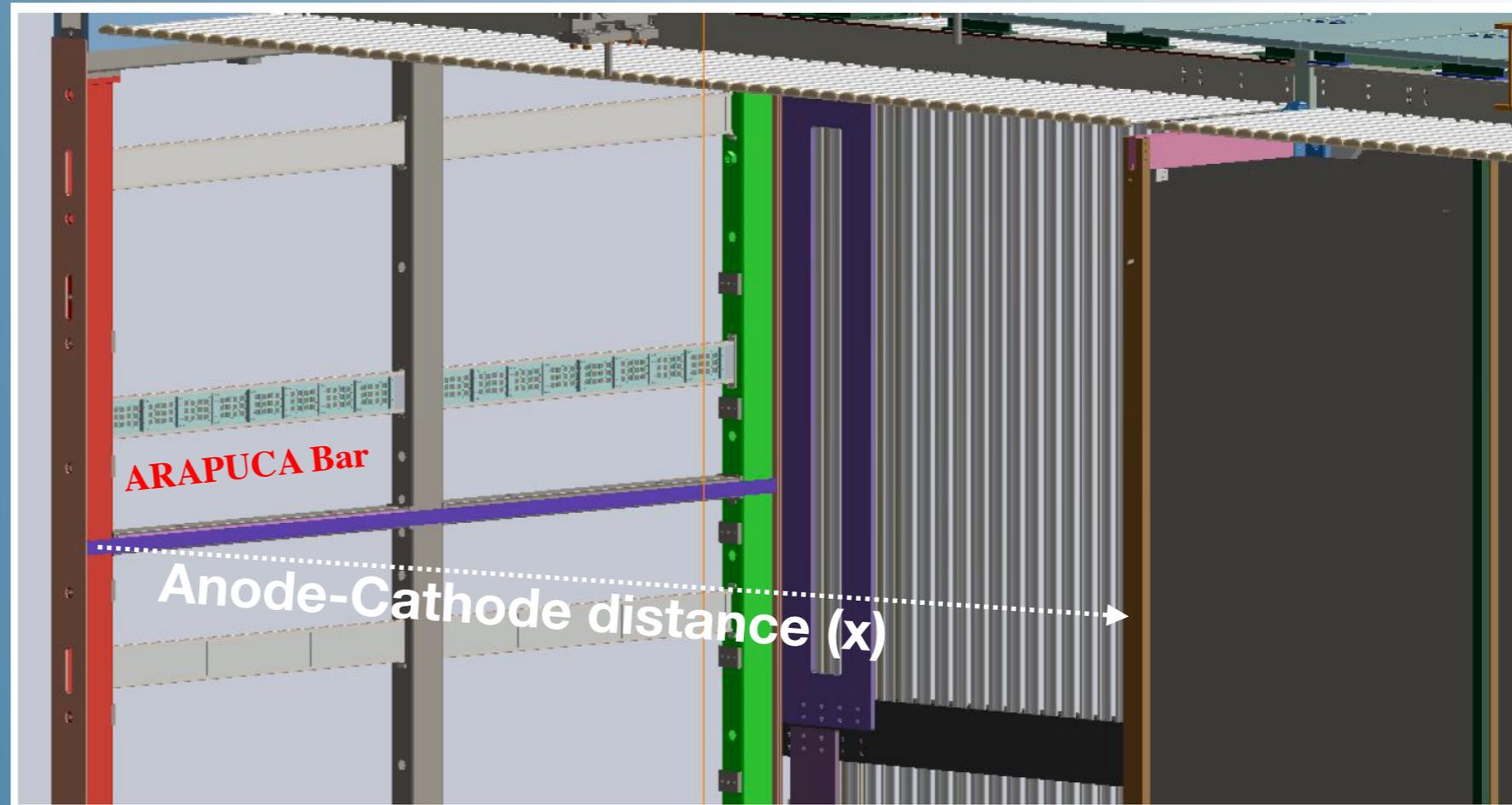
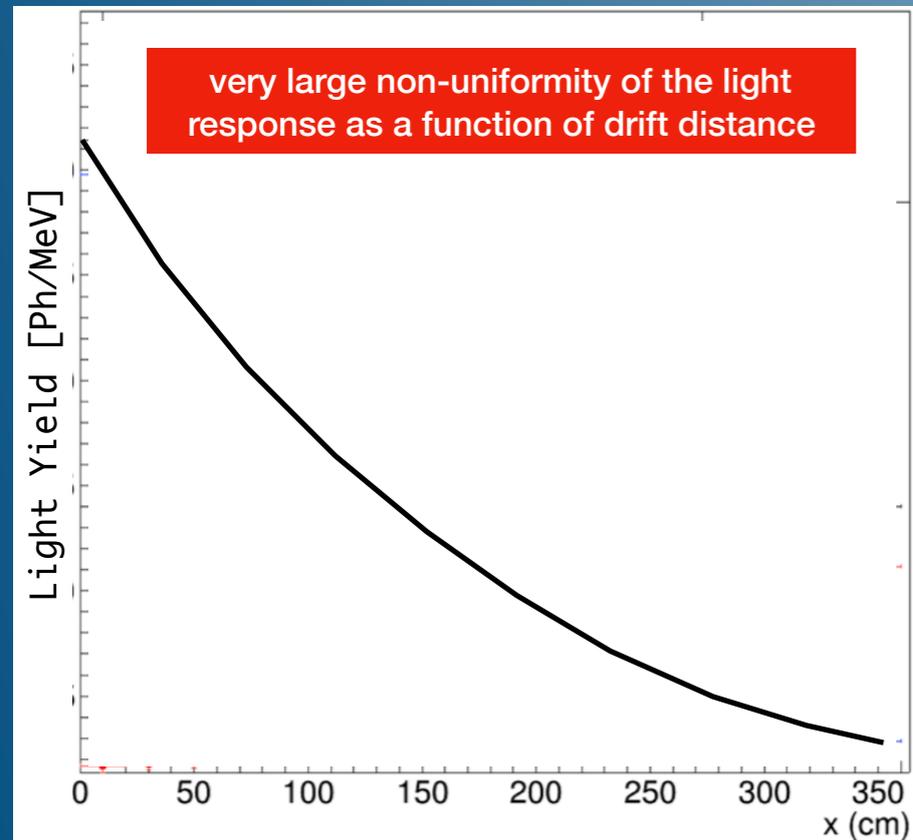
$$= \underline{38773 \text{ Ph}} \text{ (on X-ARAPUCA optical window)}$$

Efficiency: $3.4 \pm 0.2 \%$

[including corrections for LAr Purity, and for CrossTalk and After Pulses in SiPM]

Achievements so far:

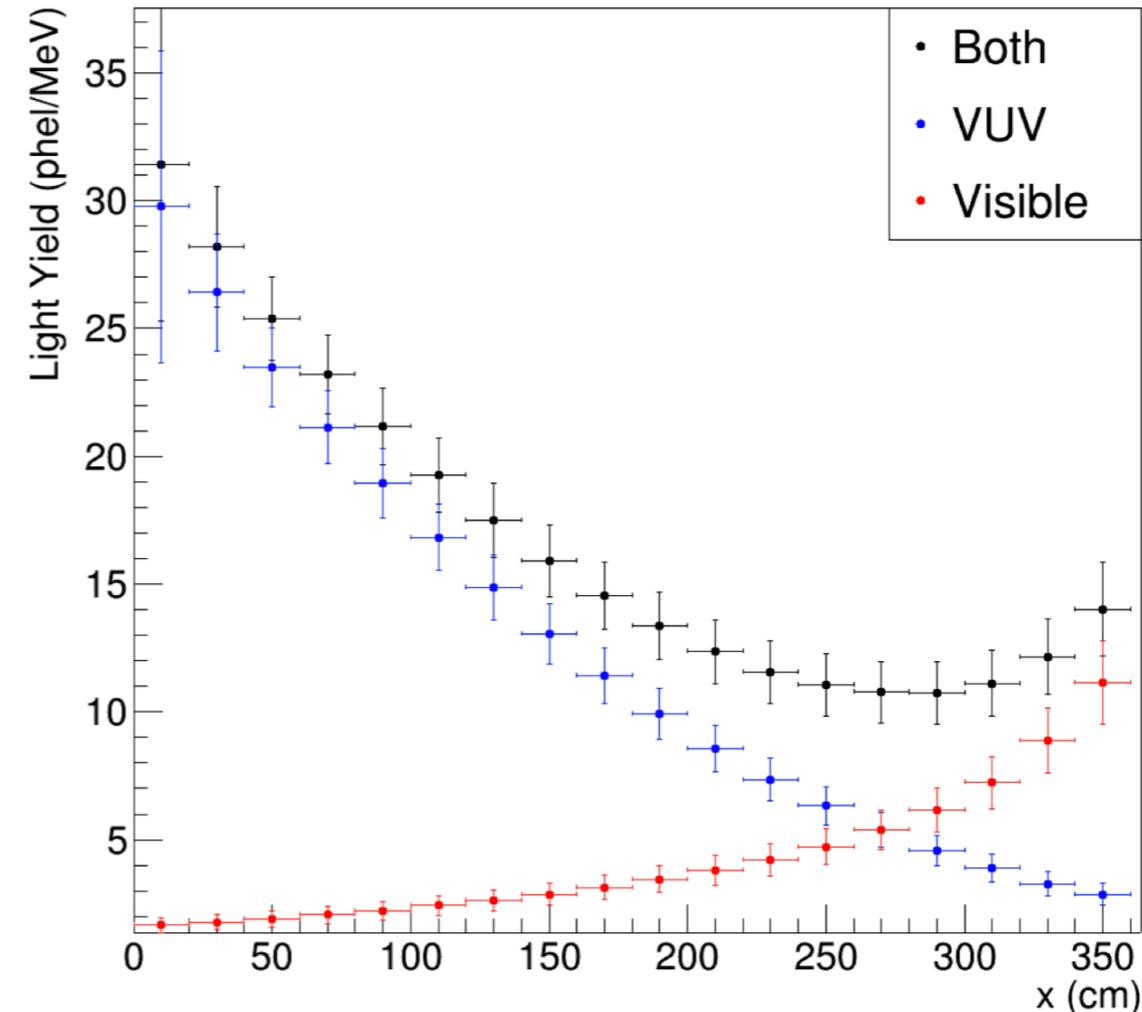
- Demonstrated enhanced Efficiency in the FEW/SEVERAL % range (with possible further optimization)
- Compatible with APA/LArTPC geometrical constraint



**Perspectives for ARAPUCA technology
in DUNE Module(s) of Opportunity**

Reflective foils in DUNE

- Wavelength-shifting reflective foils on cathode analogous to SBND is a proposed extension to the photon detection system in DUNE single-phase.
- Direct light alone results in low light yield far from anode:
 - VUV Rayleigh scattering length ~ 60 cm in LAr
 - drift distance 350 cm
- Including reflective foils improves light yield close to cathode + overall light yield uniformity in drift direction.
- Effective simulation of both components required to study contribution of reflective foils.



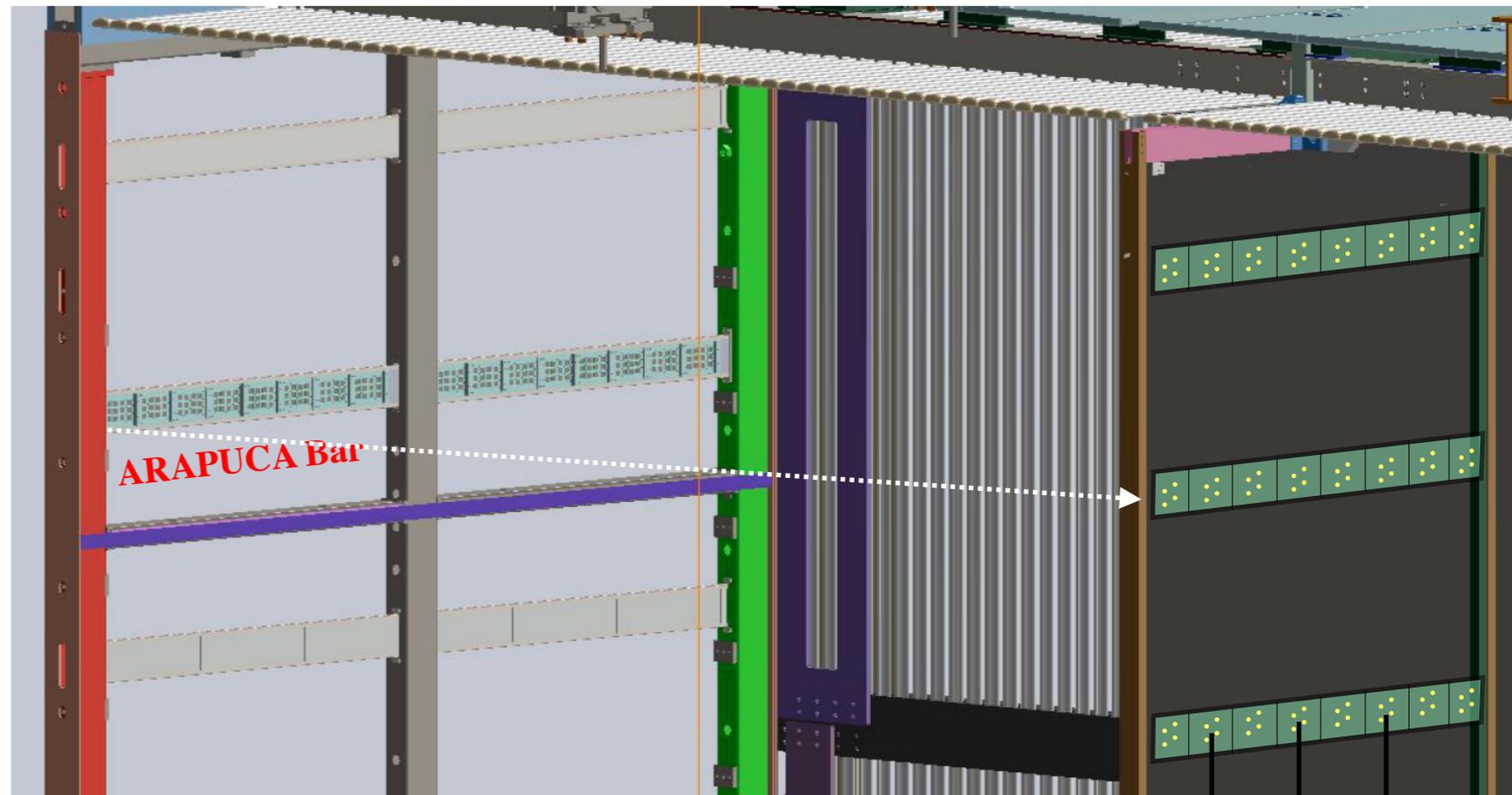
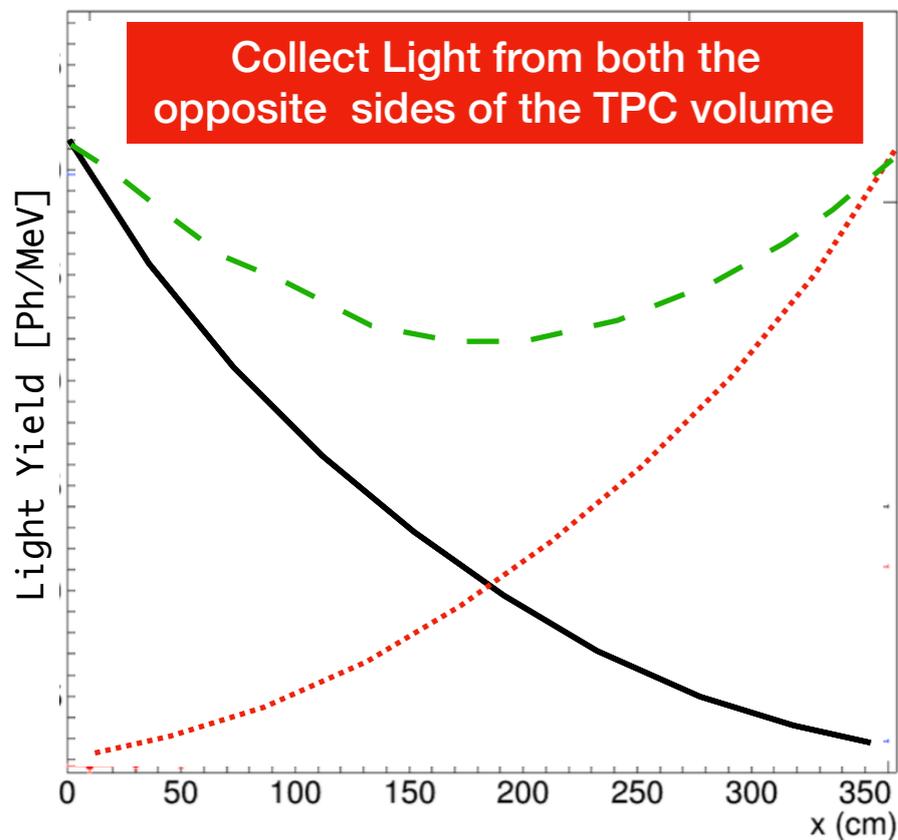
QE = 3.5%; 80% cathode foil coverage; 80% optical detectors TPB coated; 60% visible light transmittance through TPB coating

Low energy events are visible in approximately 80% of the detector volume

transform the cathode plane into a photo-sensitive cathode plane

- Collect from both the opposite sides of the TPC volume = ideal solution to:
- make the response uniform across the detector
- enhance the light yield
- improve the pointing capability/space resolution of the PDS

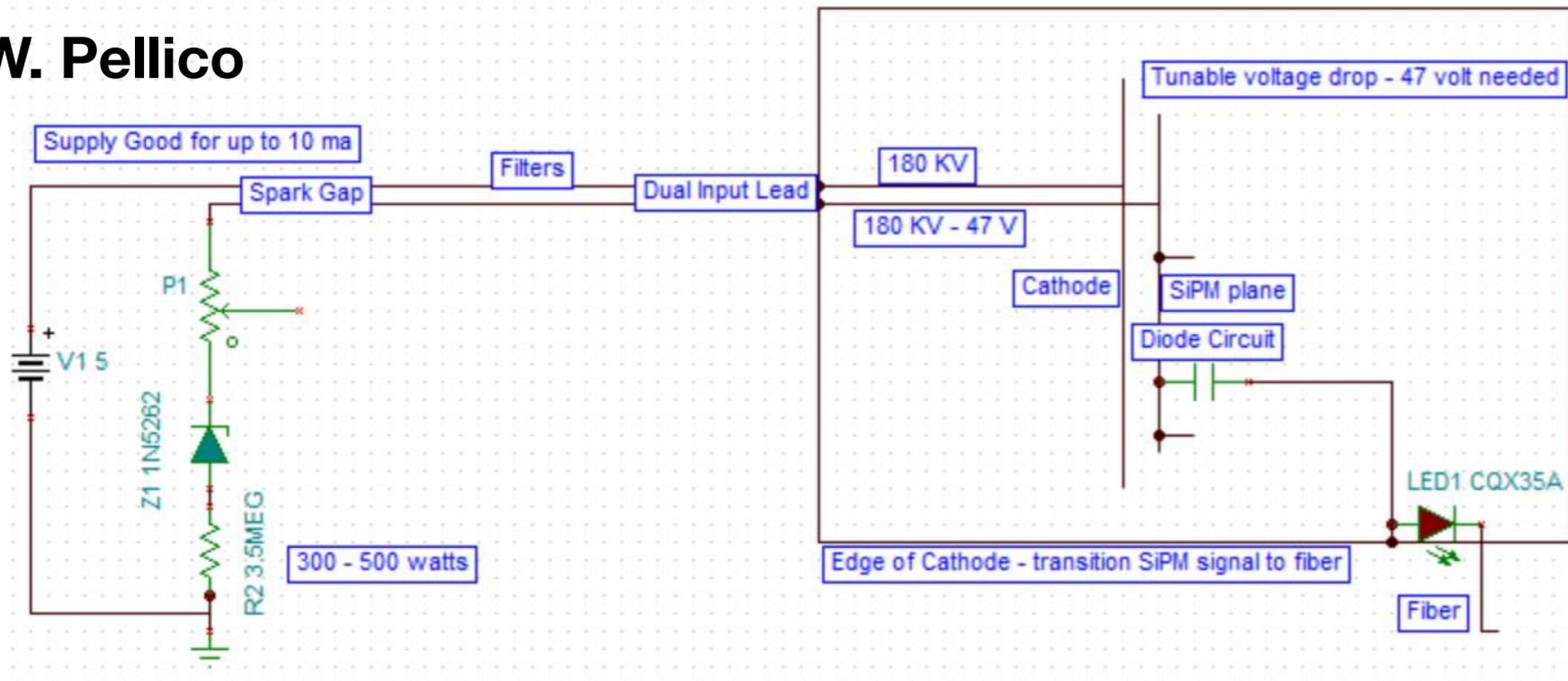
W. Pellico - F.C. (FERMILAB)



Arrays of SiPMs passively ganged in parallel to form single channels

Instrumenting with photo-sensors a surface at very large HV is a challenge that requires dedicated R&D

W. Pellico

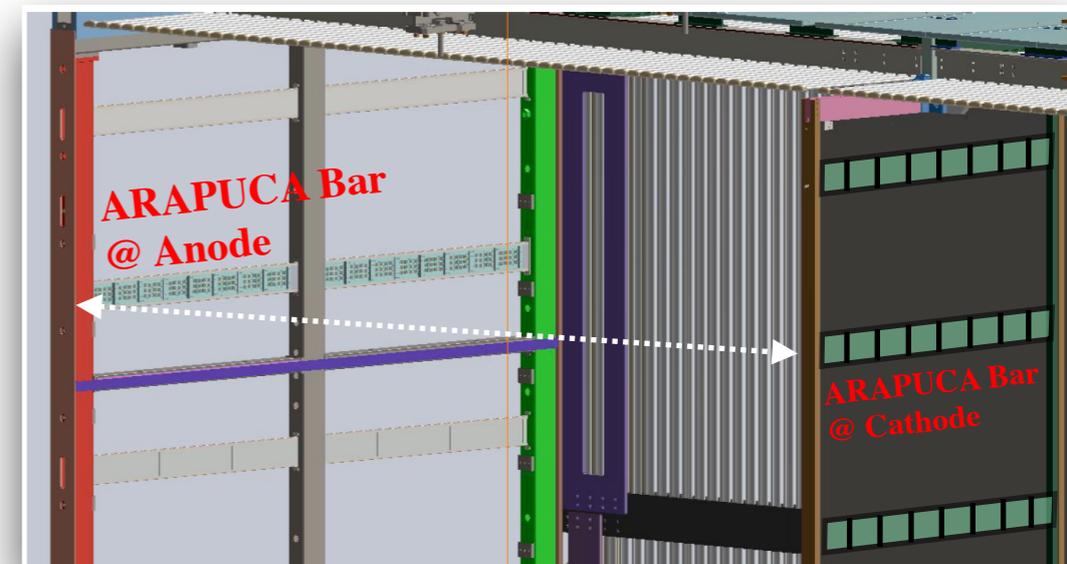


the challenge is to **supply bias voltage** (in the range of 50 V or less) and to **read-out the signal** out of the cathode plane at (nominal) 180 kV:

Bias voltage can be supplied deriving it from the voltage drop from cathode to the first field cage ring, through a dedicated passive resistor circuit.

SiPM **Analog signal** can be commuted into light signal by **optical link devices** at the edge of the cathode plane and transported outside by **optical fibre cable**.

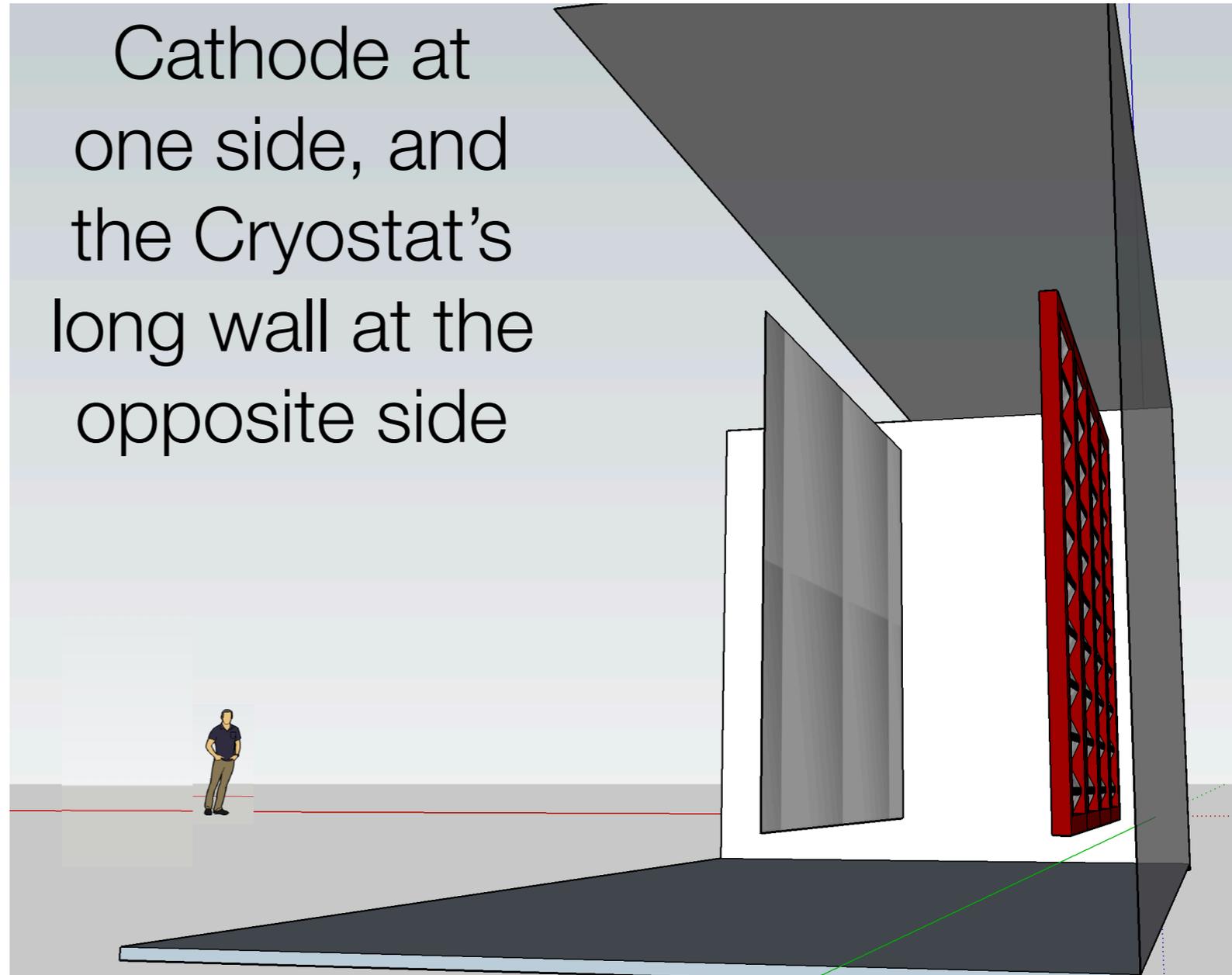
Further development can explore implementation of **photo collectors** embedded in the cathode plane: the **ARAPUCA design** looks adaptable to this purpose



About 35% of the liquid Argon in the DUNE FD Modules, around the Single Phase LArTPC volume, is inactive and used for insulation purpose only.

Thin PD modules based on ARAPUCA (X-ARAPUCA) technology can be arranged in a plane behind the APA plane and looking at events generated in the currently dead Argon volume [or using double sided ARAPUCA in APA frame - as for the inner APAs]

External APAs face the Cathode at one side, and the Cryostat's long wall at the opposite side



Courtesy P. Debbins, Y. Onel (U. Iowa)

F.C. (FNAL)

Detector Support Structure

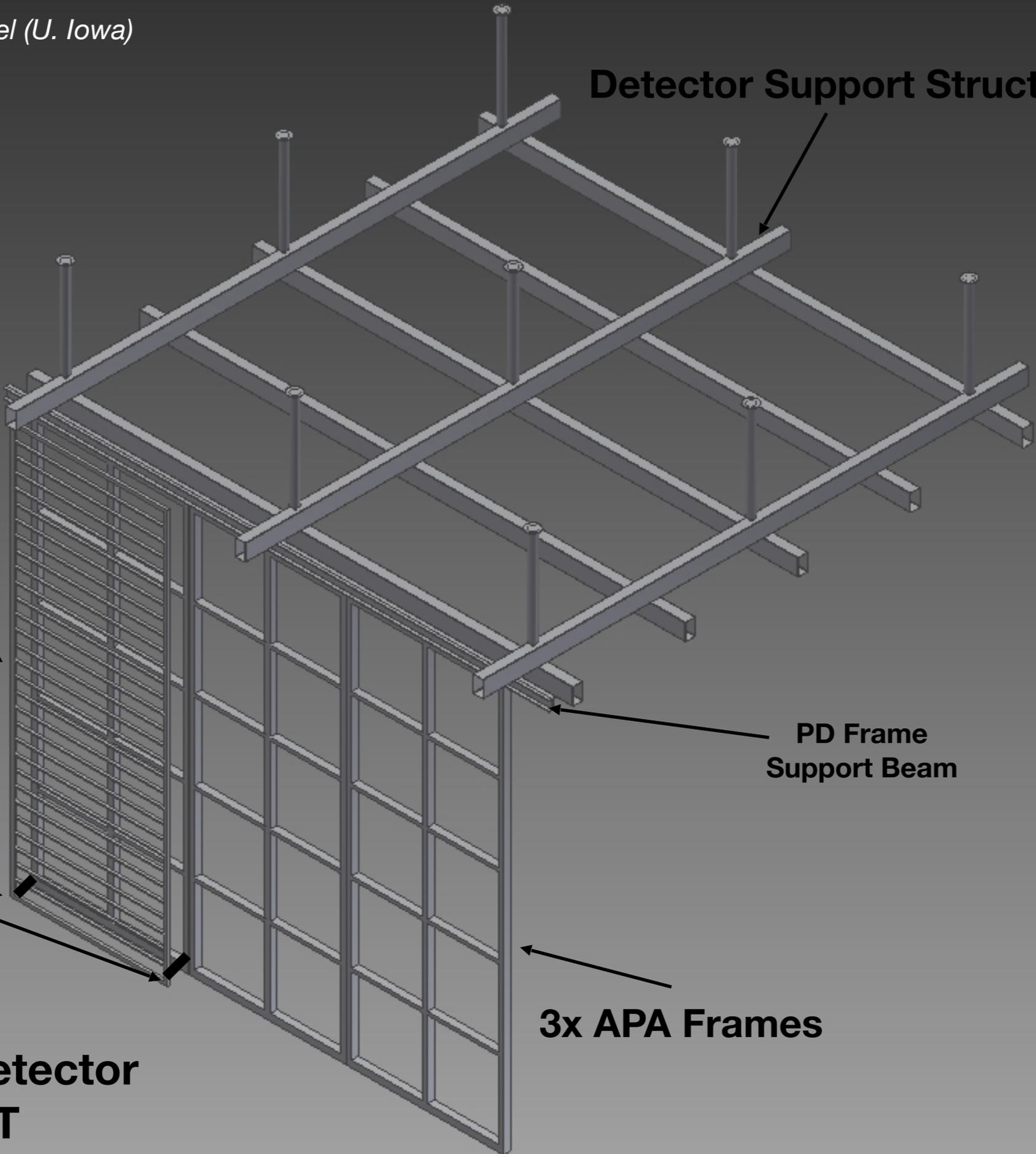
Single Photo Detector Frame

PD Frame Support Beam

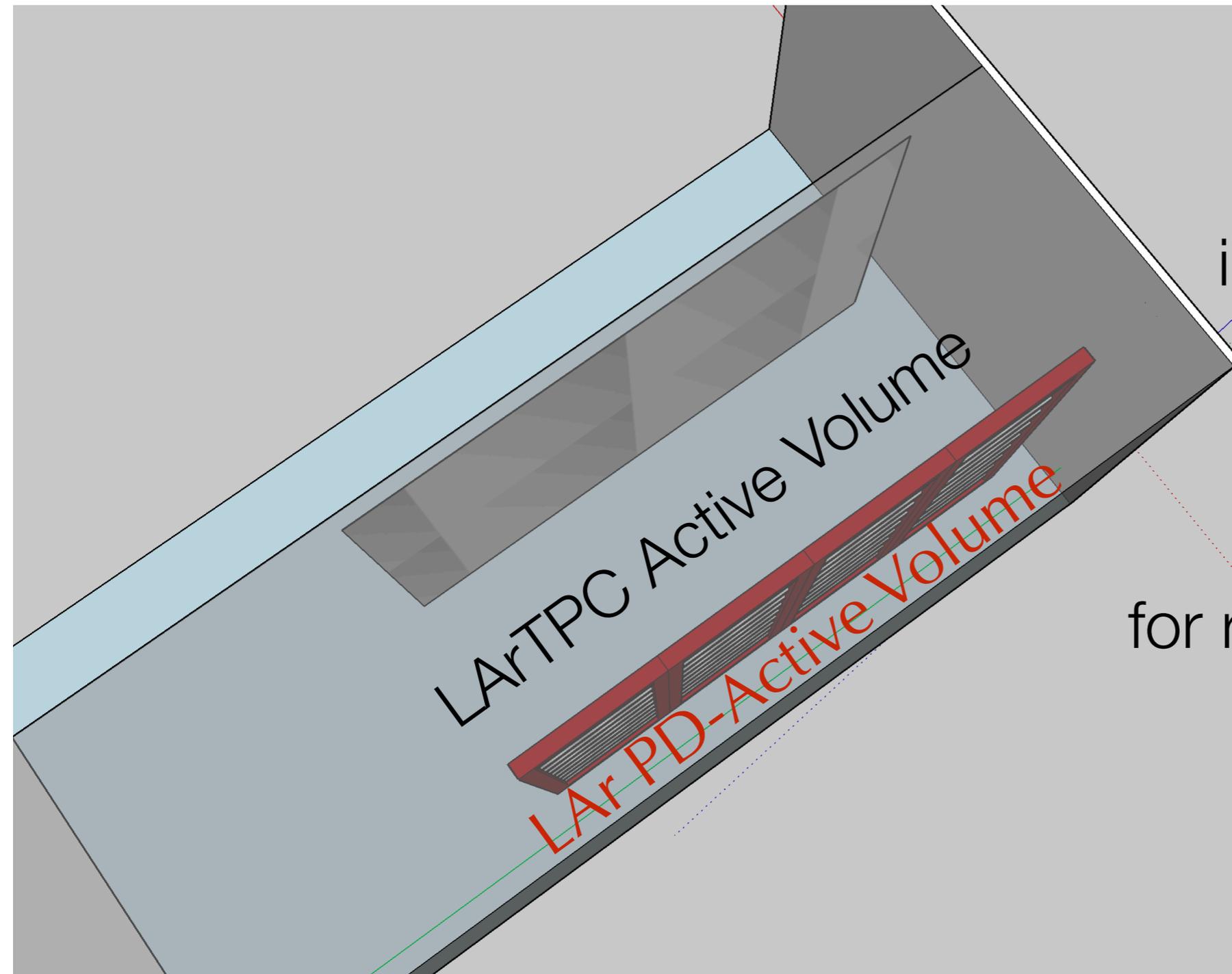
2x Frame Standoffs

3x APA Frames

DUNE
Large Photo Detector
CONCEPT



TWO-sided PD System



promotes
the large outer
dead-LAr Volume
into a *PD-Active* LAr
Volume,
acting as VETO
(*background rejection*)
for rare underground signal
searches
[e.g. p-decay] and
increasing detection
capability of SN event.

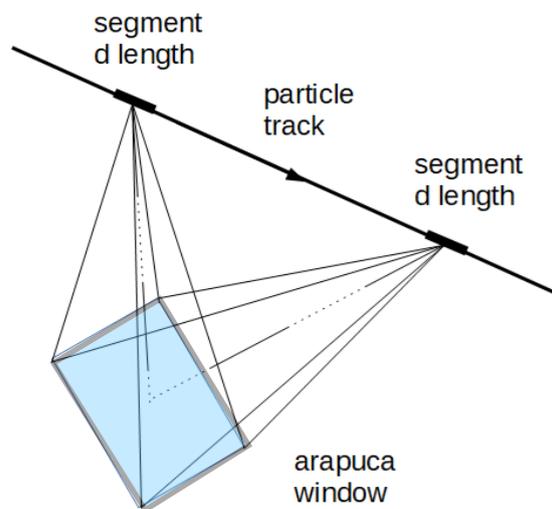
No advanced R&D is required for the detector technology as the one already selected for the active TPC volume is appropriate for this application

SUMMARY

- A new Light Collection Technology Concept - light trapping by dichroic filter coupled w/ two wls stages [ARAPUCA] - proposed for DUNE in Summer 2016 (PD System Review)
- First ARAPUCA prototype test in Fall 2016 at LNLS (Brazil) - with α source and c.r.muons \Rightarrow **Efficiency Measurement**
- Detector design developed for ARAPUCA integration in APA/DUNE and test in Fall 2017 at FNAL (TallBo test facility) with c.r.muons \Rightarrow **Efficiency Measurement**
- ARAPUCA bars in protoDUNE: test with charged particle beams (e , π , p) Sept-Nov 2018). First **Calorimetric Energy Measurement** - Long duration test w/ c.r.muons 2019.
- ARAPUCA Technology development: X-ARAPUCA with enhanced efficiency - Installation in SBND detector
- Perspectives for Module of Opportunity:
 - ★ Photo-sensitive Cathode Plane
 - ★ dead-LAr Volume into a *PD-Active* LAr Volume

Illumination and Efficiency

- The illumination - PH , number of photons which arrive at the ARAPUCA cell optical window - is estimated for each track as the product of the track **integrated angular Acceptance** (over the track length) and the number of emitted photons per unit length and unit solid angle.



$$PH = A_{\Omega} \frac{1}{4\pi} \frac{dN^{\gamma}}{dx}$$

$$\frac{dN^{\gamma}}{dx} = Y_{\gamma} q_{mip} \left\langle \frac{dE}{dx} \right\rangle_{\mu} \rho_{Ar}$$

$$A_{\Omega} = d \sum \Omega_i$$

- The **Efficiency** - Total or Individual (for the i -cell) - can be defined as the ratio between the photoelectrons measured by the detector and the estimated photons impinging upon the optical surface.

$$\epsilon_{TOT} = \frac{\sum PE_i}{\sum PH_i}$$

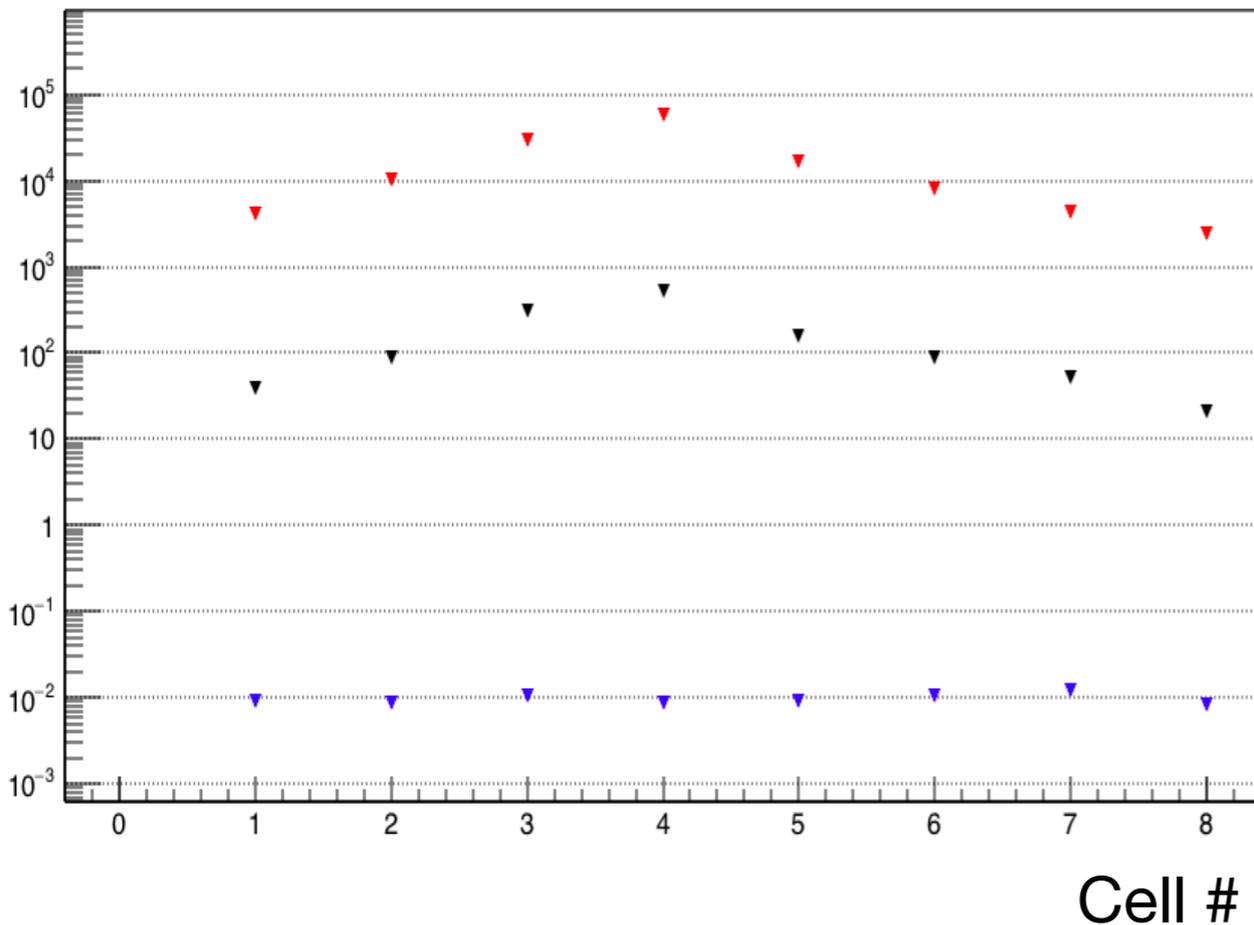
$$\epsilon_i = \frac{PE_i}{PH_i}$$

- The efficiency is an intrinsic characteristic of the detector it is independent from the photons landing and from the track.

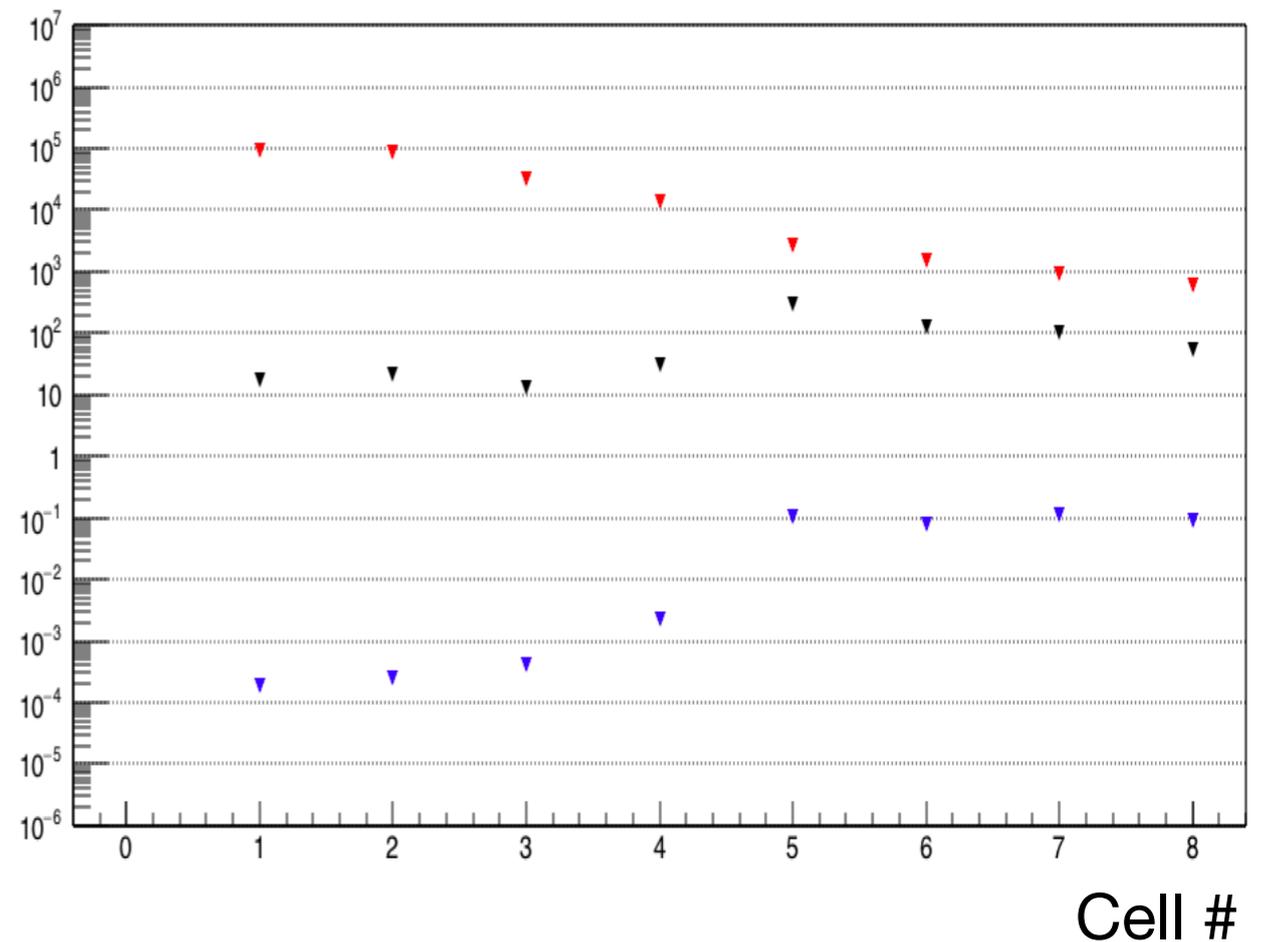
Light Pattern in ARAPUCA PD system (Cells 1 to 8)

The segmentation of the ARAPUCA PD system provides very powerful (additional) handle for Signal from Background identification: for each trigger, reconstruct the **pattern** of the detected light $\{PE_i\}$ in the Cells and compare with the expected illumination $\{PH_i\}$ from the triggered track.

$\{PE_i\} \propto \{PH_i\}$: Signal (muon track) event

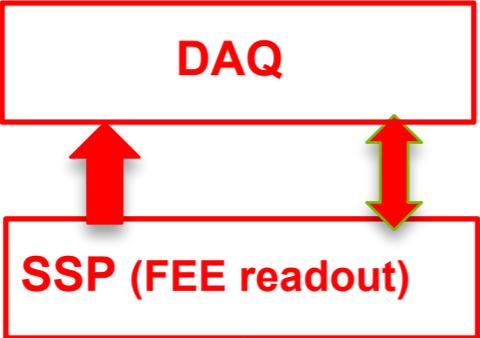


inconsistent light pattern: Background event

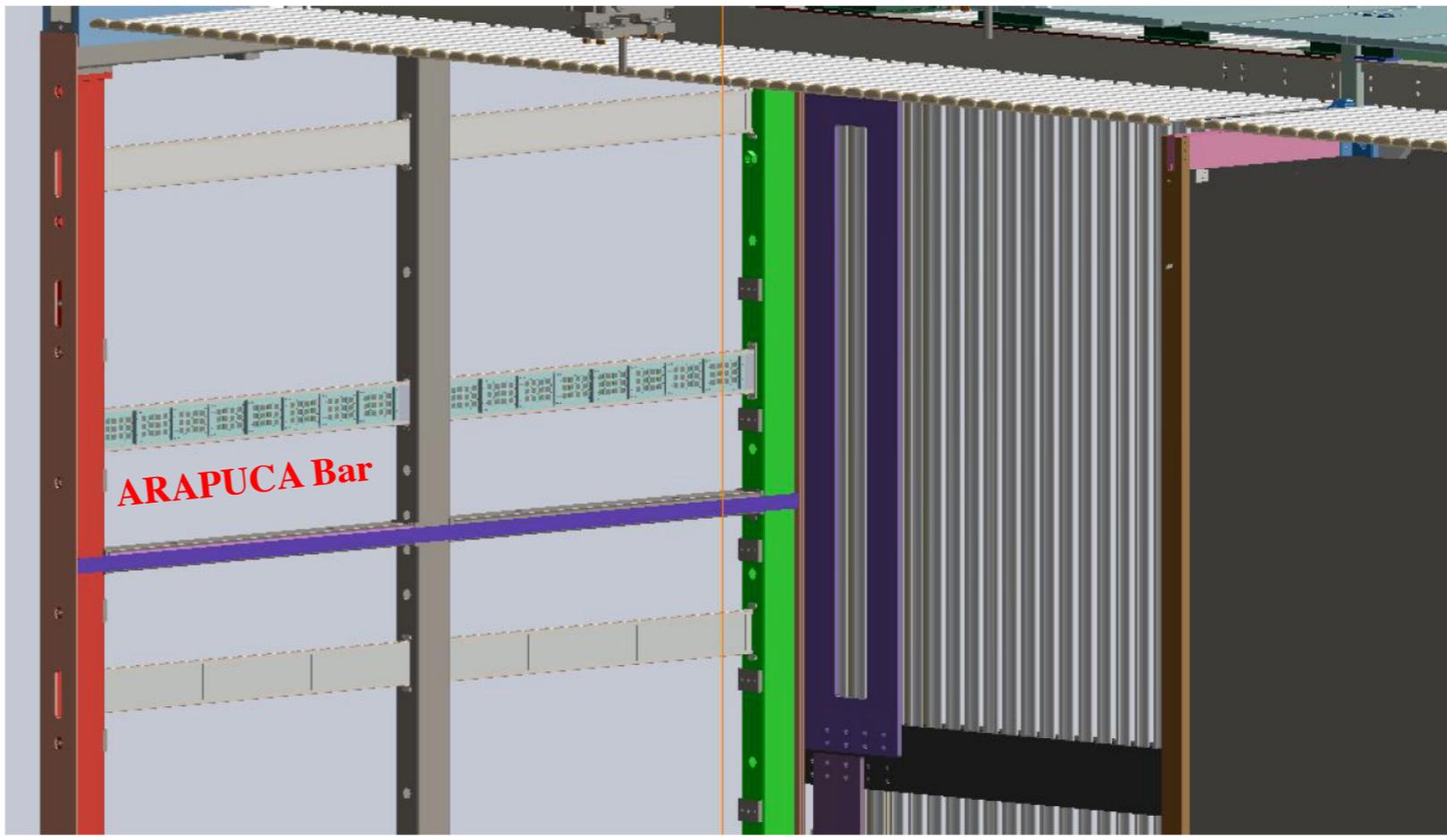
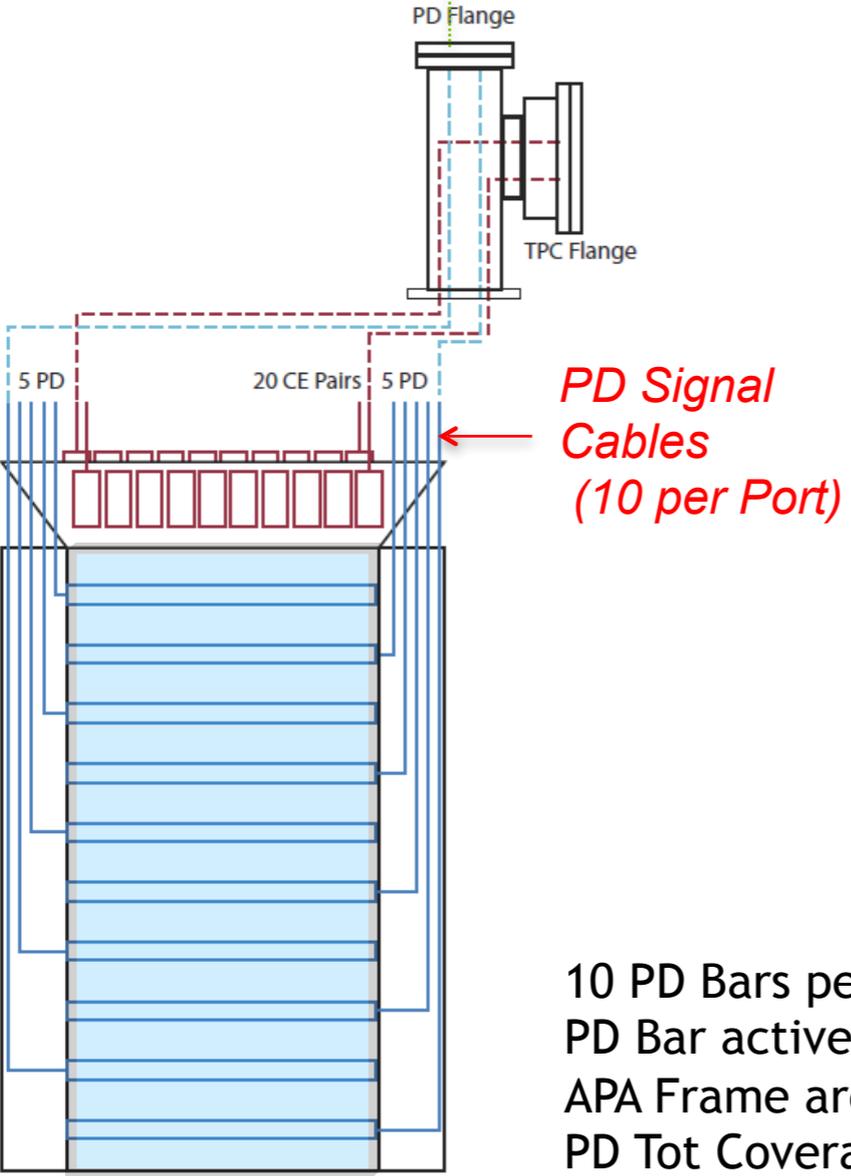


Photon Detection System Design in protoDUNE Single Phase

- Three PD technologies implemented:
 - ARAPUCA Light Trap
 - Dip-Coated Light Guide
 - Double-Shift Light Guid



PD Modules (Bars) mounted in APA Frame

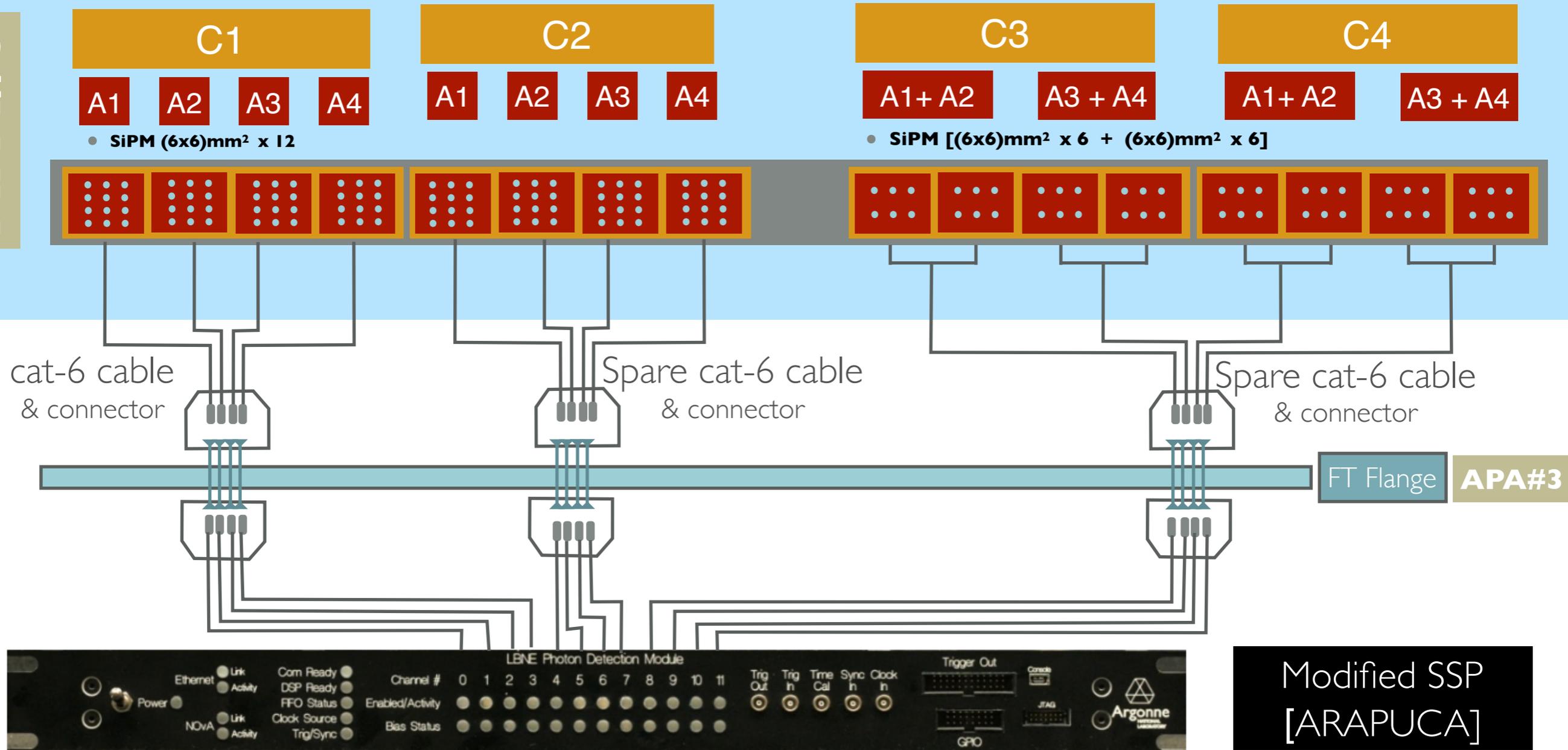


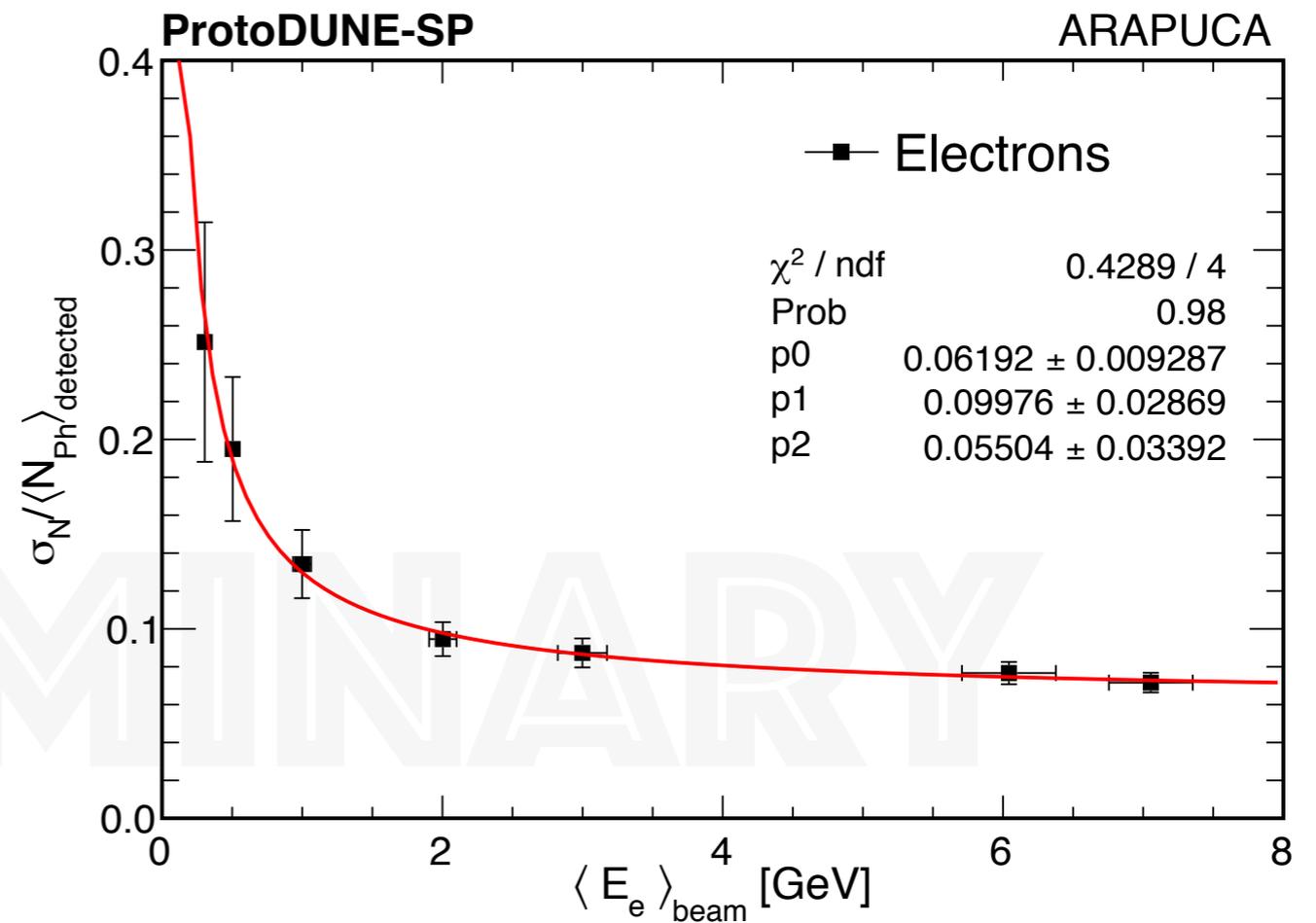
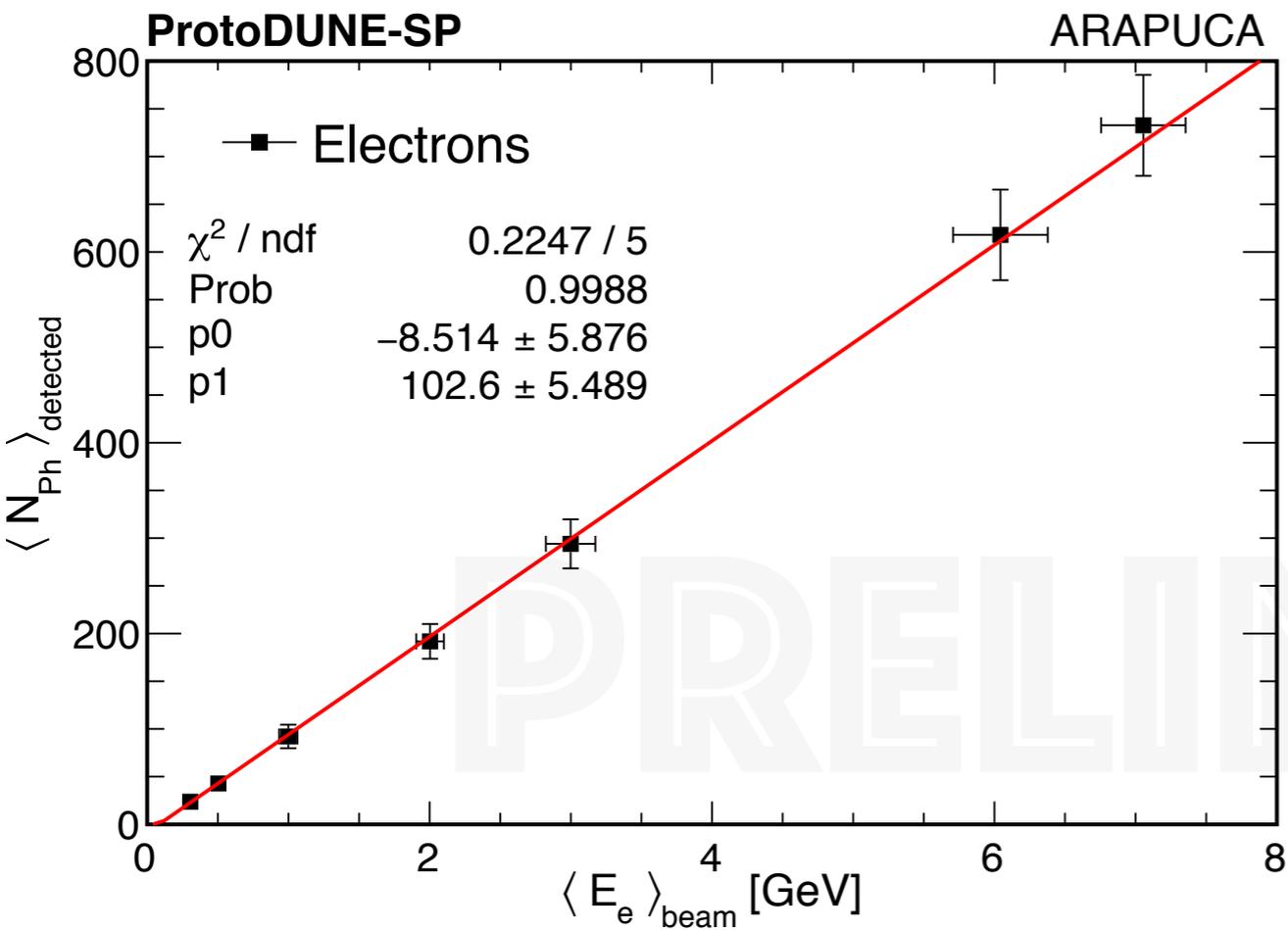
10 PD Bars per APA Frame
 PD Bar active area: Light Guide Bar 1744 cm² - ARAPUCA Bar 1223 cm²
 APA Frame area (Outside) 6060mm X 2300mm
 PD Tot Coverage fraction: ~12.5%

SiPM in ARAPUCA Cells and read-out

LAr

APA#3





Linearity

of light response over the entire range of energies.

The slope gives the light yield

$$LY = 103 \text{ Ph/GeV}$$

from (only) one ARAPUCA module, relative to a diffused light source (EM shower) at a distance of about 3 m

Energy Resolution from light

$$\frac{\sigma_E}{E} = p_0 \oplus \frac{p_1}{\sqrt{E}} \oplus \frac{p_2}{E}$$

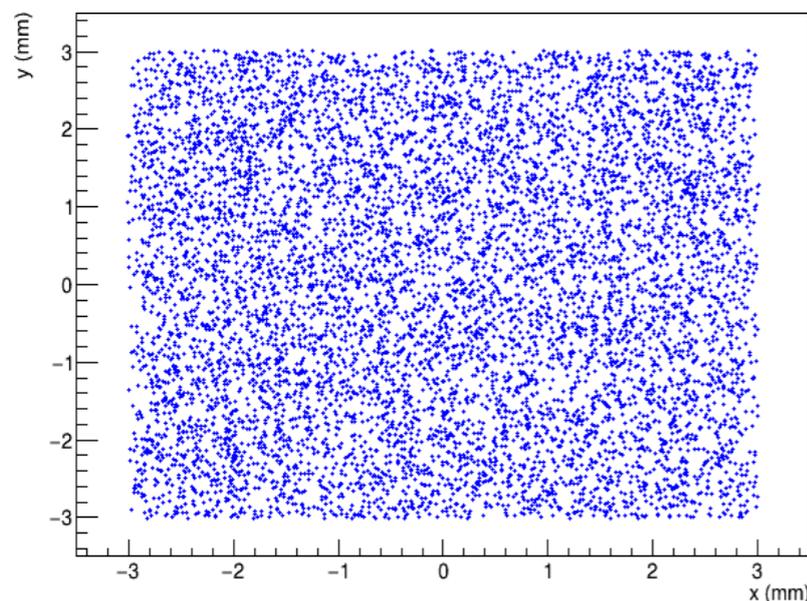
- **Stochastic term:** $p_1 = 10\%$
from limited photo-sensitive area coverage
- **Noise term:** $p_2 = 55 \text{ MeV}$
from excellent SiPM readout S/N ratio
- **Constant term:** $p_0 = 6.2\%$
from non-uniformities in light collection (from one side only)

MC Comparison X-Arapucas and S-Arapucas

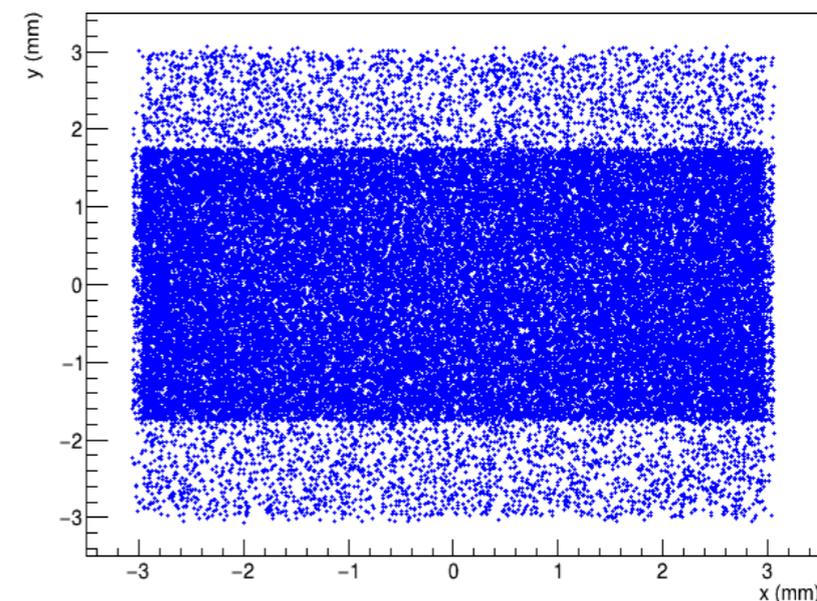
- **Response Simulation**

Efficiency improvement of 15 – 40% (for test @ Unicamp) - up to 55% more photons in slab region

S-Arapuca

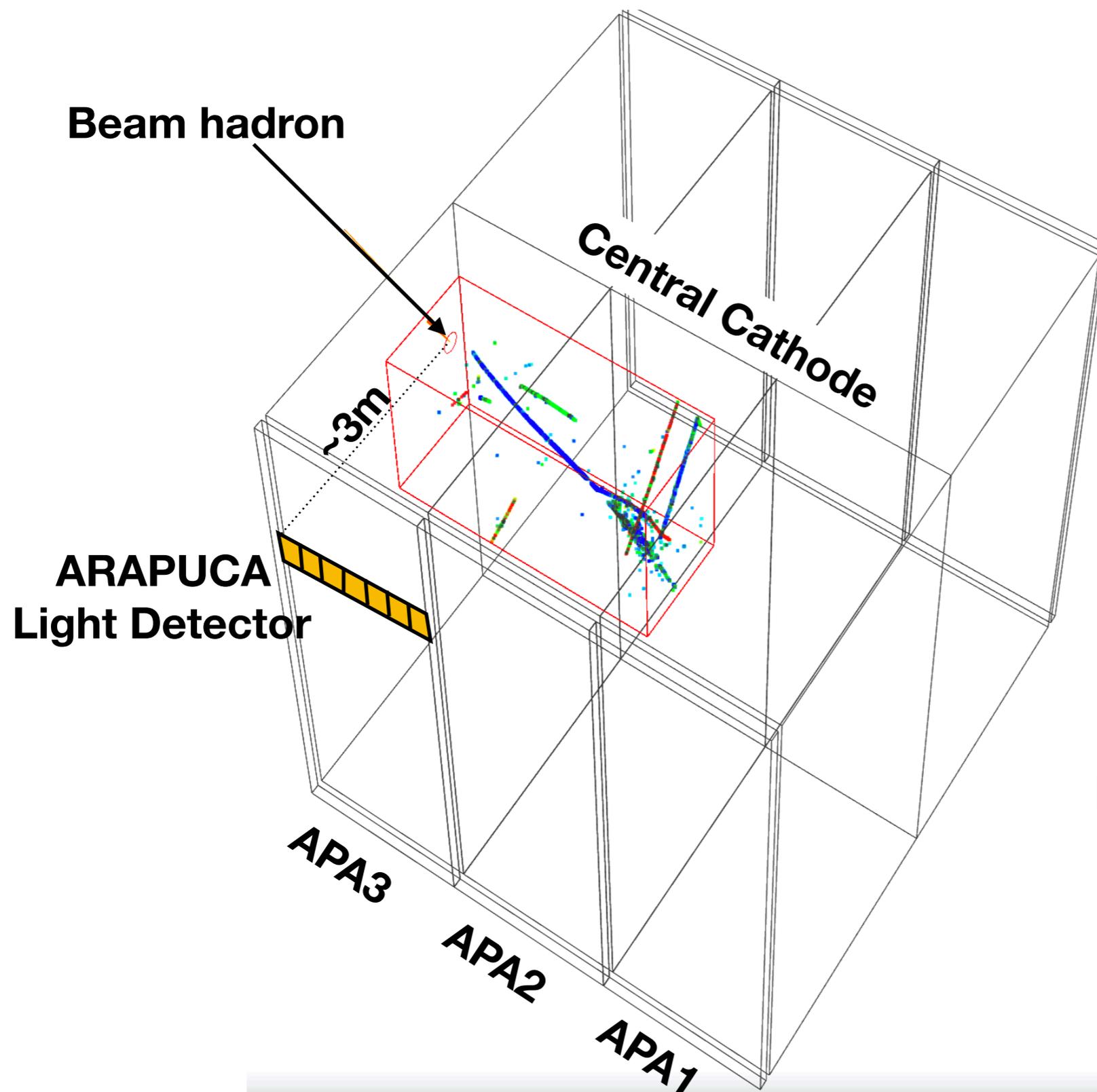


X-Arapuca



No gap between bar and SiPM
No attenuation for the bar

Test Beam Run (in progress): 1 - 7 GeV Momentum Charged Particle (e, had) Beams

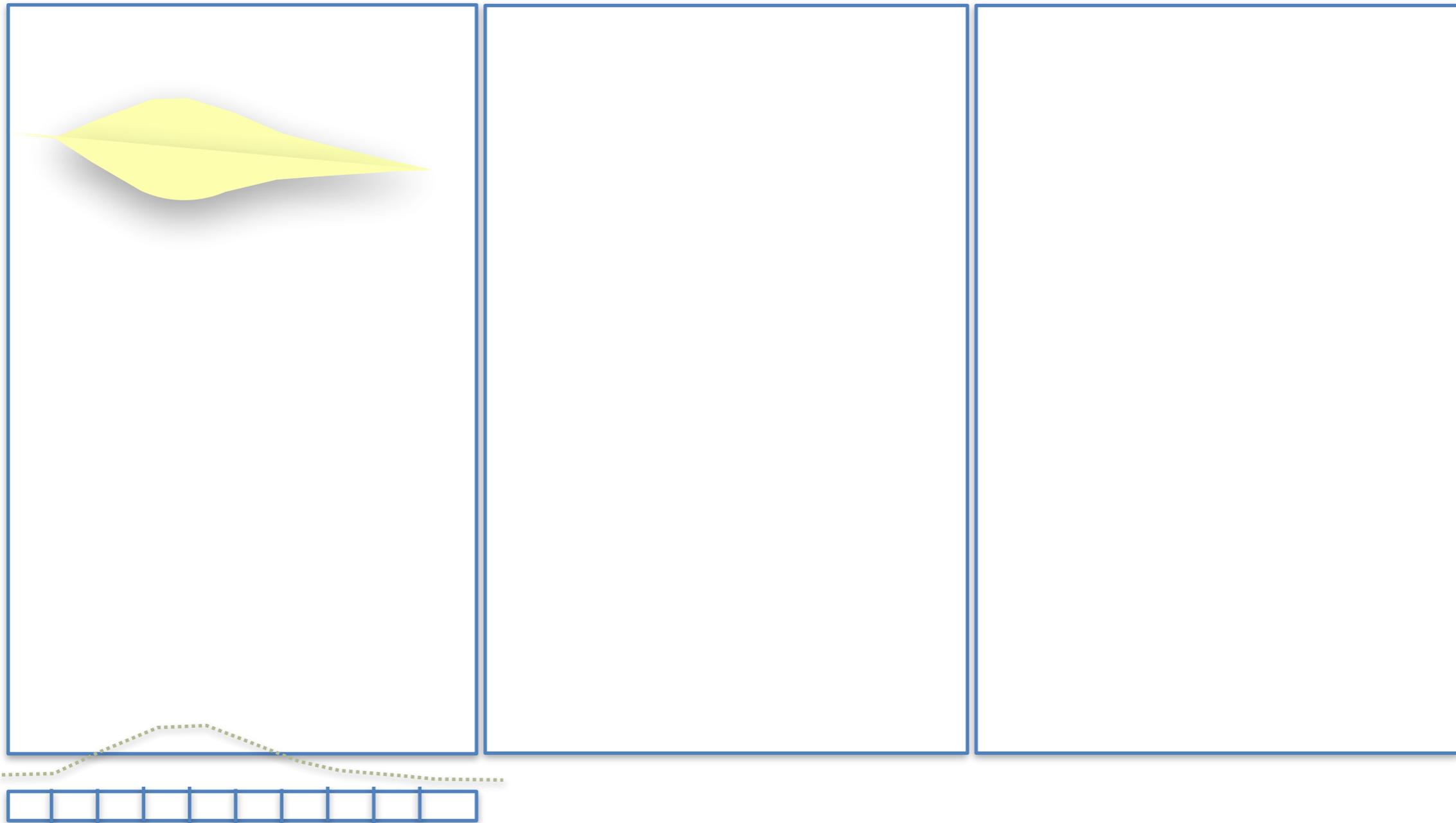


Scintillation Light
from Energy
deposited by beam
hadrons or electrons
in LAr
detected by
ARAPUCA
[at ~3m distance]

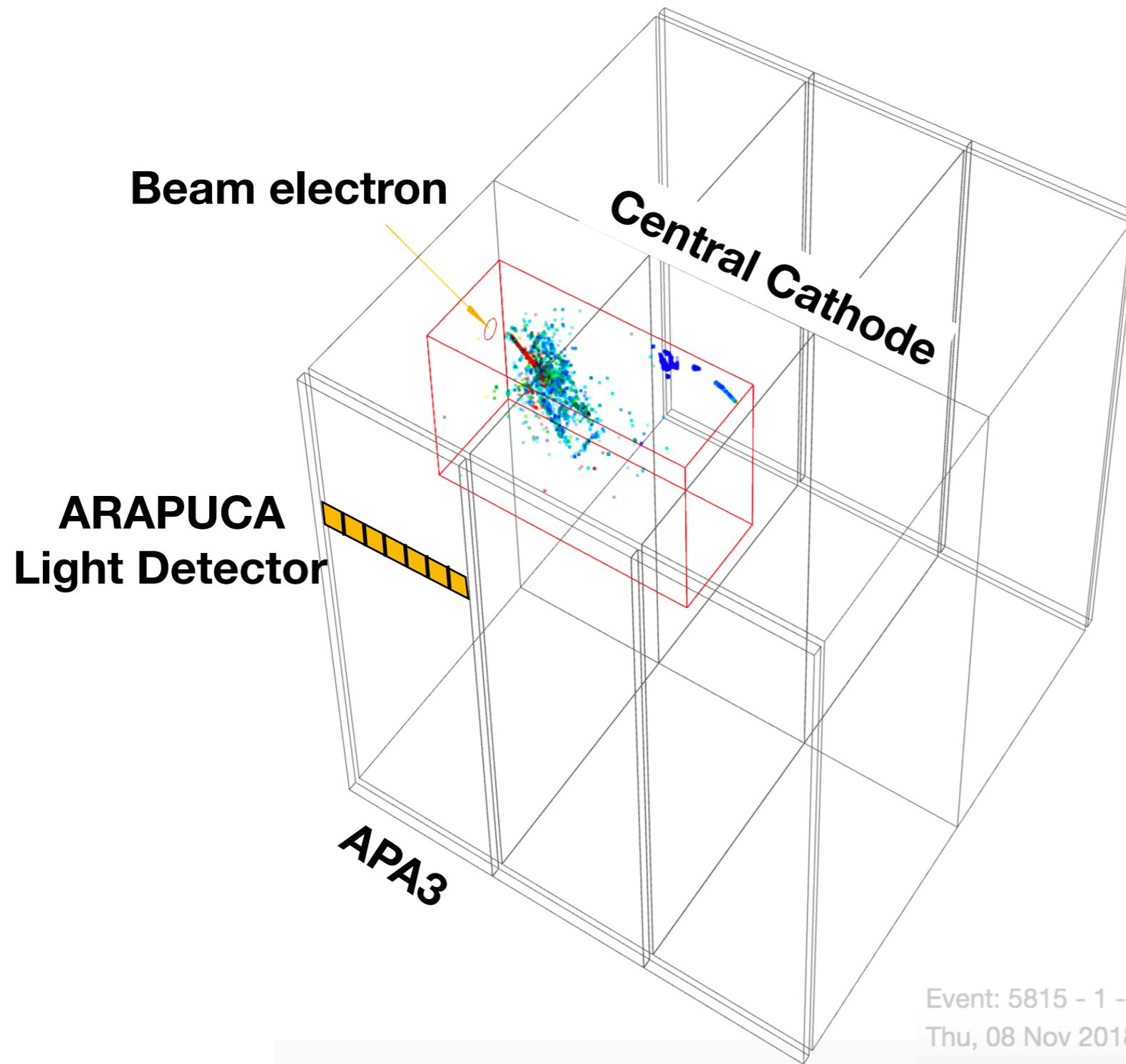
Beam Particle Energy tunable
in 1-7 GeV range

EM Shower

PDS RESPONSE



Test Beam Run (in progress): 1 - 7 GeV Momentum Charged Particle (e, had) Beams



**Scintillation Light
from Energy
deposited by beam
hadrons or electrons
in LAr
detected by
ARAPUCA
[at ~3m distance]**

Note: electron

Event: 5815 - 1 - 24552 | trigger: 12
Thu, 08 Nov 2018 17:40:52 +0000 (GMT) + 0 nsec

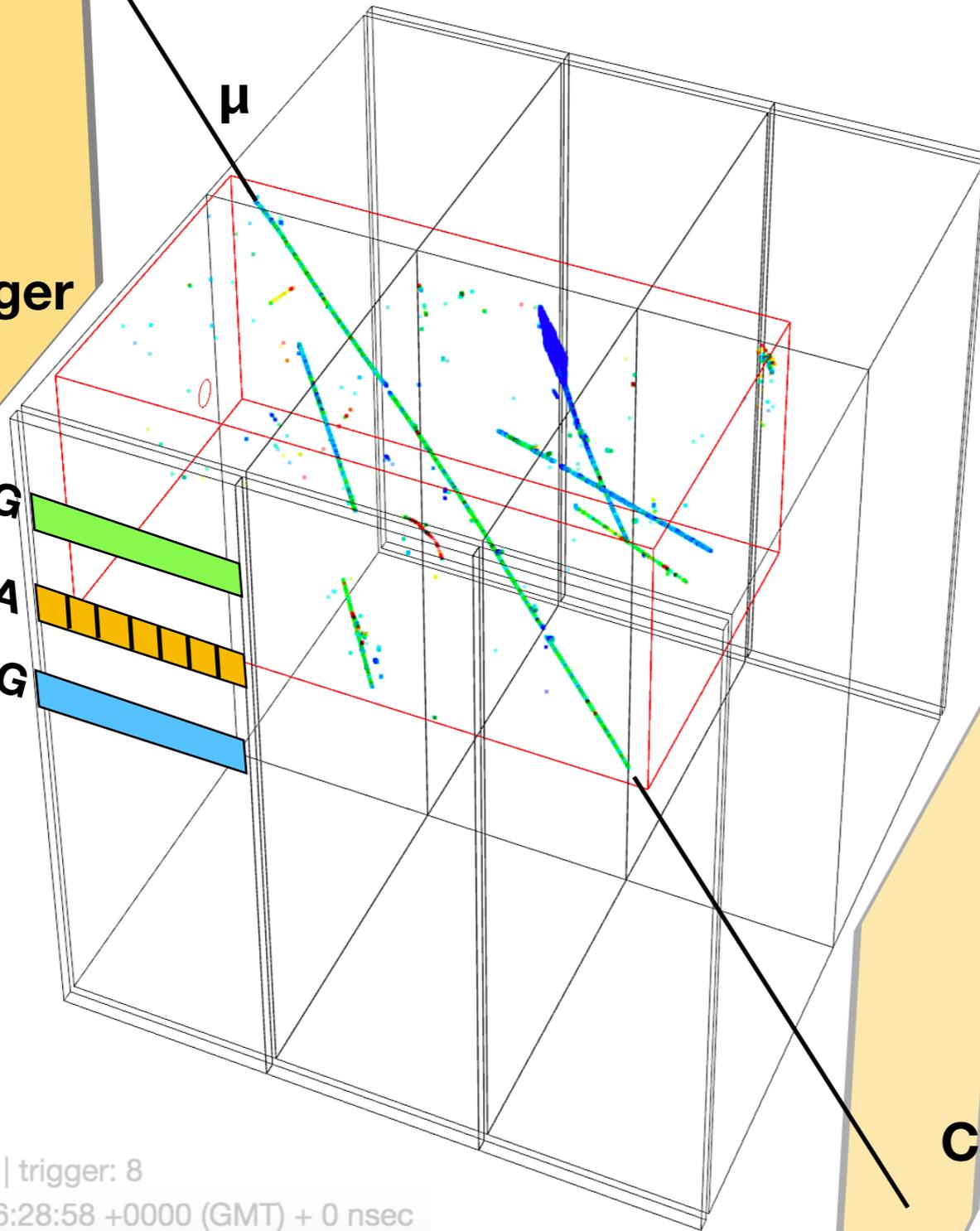
Cosmic Muon (long duration run - starts on Nov 12)

Cosmic Muon Tagger

double-shift LG

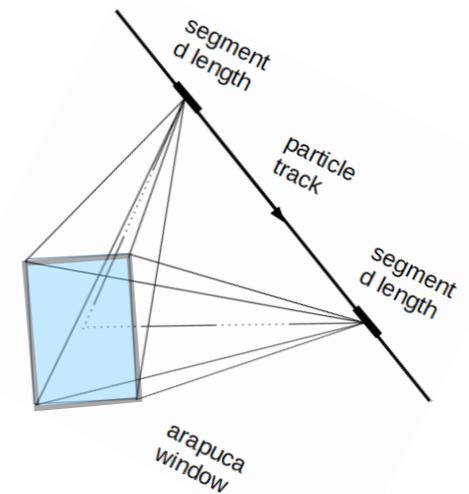
ARAPUCA

dip-coated LG



Comparative Efficiency (PE/PH) Measurement to be performed with Muon Tracks from CRT trigger

$$PH = A_{\Omega} \frac{1}{4\pi} \frac{dN^{\gamma}}{dx}$$

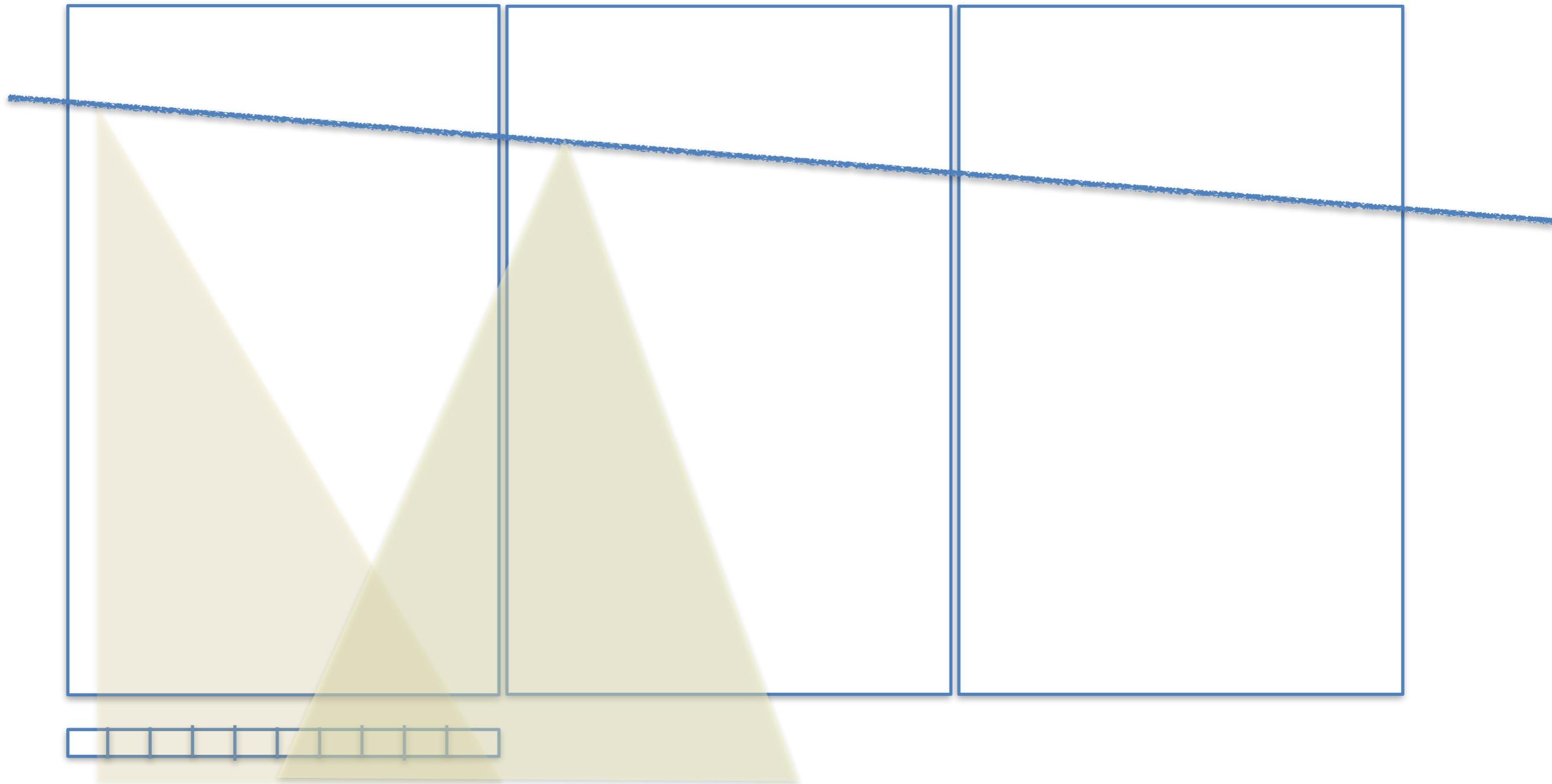


Cosmic Muon Tagger

Event: 5815 - 1 - 21 | trigger: 8
Thu, 08 Nov 2018 16:28:58 +0000 (GMT) + 0 nsec

Crossing Muon

PDS RESPONSE



Alpha to Muon separation

Light source: Scintillation in LAr from Alpha particles and Cosmic Muons

Exploit pulse shape capabilities of LAr to discriminate and analyze separately the α and the μ samples and obtain two independent estimations of the ARAPUCA efficiency

$$F_{\text{prompt}} = \frac{\int_{t_0}^{t_0+1500 \text{ ns}} I(t) dt}{\int_{t_0}^{t_0+10000 \text{ ns}} I(t) dt}$$

